Analysis of Drifting SOFAR Buoys

in the Greenland Sea 1989-1990

by

David Hilton McCarren
Lieutenant Commander, United States Navy
B.S., Pennsylvania State University, 1979

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN METEOROLOGY

AND PHYSICAL OCEANOGRAPHY

from the

NAVAL POSTGRADUATE SCHOOL
December 1991

Jnclassified

CURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/ AVAILABILITY OF REPORT Approved for public release; distribution is unlimited.
DCLASSIFICATION/DOWNGRADING SCHEDULE	
PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S)
NAME OF PERFORMING ORGANIZATION Naval Postgraduate School — 6b. OFFICE SYMBOL *(If Applicable)*	7a. NAME OF MONITORING ORGANIZATION Naval Postgraduate School
ADDRESS *(city, state, and ZIP code)* Monterey, CA 93943-5000	7b. ADDRESS *(city, state, and ZIP code)* Monterey, CA 93943-5000
NAME OF FUNDING/SPONSORING ORGANIZATION — 6b. OFFICE SYMBOL *(If Applicable)*	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
ADDRESS *(city, state, and ZIP code)*	10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NC

TITLE *(Include Security Classification)*

ANALYSIS OF DRIFTING SOFAR BUOYS IN THE GREENLAND SEA 1989-1990

PERSONAL AUTHOR(S)
McCarren, David H.

TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT *(year, month,day)*	15. PAGE COUNT
Master's Thesis	FROM TO	December 1991	84

SUPPLEMENTARY NOTATION
The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

COSATI CODES			18. SUBJECT TERMS *(continue on reverse if necessary and identify by block number)*
FIELD	GROUP	SUBGROUP	Greenland Sea, East Greenland Current, Jan Mayen Current, SOFAR floats, Fram Strait

ABSTRACT *(Continue on reverse if necessary and identify by block number)*

In an attempt to gain a better understanding of the intermediate depth circulation of the Greenland Sea, 16 SOFAR floats were launched into Fram Strait in 1988 and 1989. Between the fall of 1989 and the summer of 1990, five of these floats were tracked by autonomous listening stations (ALS) positioned to provide tracking in the southern portion of the Greenland Sea. One float (MZ86) provided tracking information for ten months of the ALS deployment period. The other floats provided tracking information ranging from several days to two months. These float tracks delineated the intermediate depth circulation around the Greenland Sea gyre. The MZ86 trajectory exited the Boreas Basin and crossed the Greenland Fracture Zone with a speed of approximately 17 cm s^{-1}. Along the Greenland continental slope the flow increased to 28 cm s^{-1} suggesting the presence of a bottom trapped boundary current. Near 74°N the trajectory turned eastward under the shallower warm core of the Jan Mayen Current at 4 cm s^{-1}. This leg closed the Greenland Sea gyre and also shows evidence of interactions with filaments of the Norwegian Atlantic Current (NAC) coming through the Mohns Ridge at these intermediate depths. Two other floats demonstrated tracks which crossed the Mohns Ridge and drifted farther to the east, mixing with the waters of the NAC.

DISTRIBUTION/AVAILABILITY OF ABSTRACT UNCLASSIFIED/UNLIMITED ☐ SAME AS T. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
NAME OF RESPONSIBLE INDIVIDUAL R. H. Bourke	22b. TELEPHONE (Include Area Code) (408) 646-3270 — 22c. OFFICE SYMBOL OC/BF

FORM 1473, 84 MAR — 83 APR edition may be used until exhausted — SECURITY CLASSIFICATION OF THIS PAGE

All other editions are obsolete — Unclassified

NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

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David H. McCarren

December 1991

Thesis Advisors: J. C. Gascard
R. H. Bourke

ABSTRACT

In an attempt to gain a better understanding of the intermediate depth circulation of the Greenland Sea, 16 SOFAR floats were launched into Fram Strait in 1988 and 1989. Between the fall of 1989 and the summer of 1990, five of these floats were tracked by autonomous listening stations (ALS) positioned to provide tracking in the southern portion of the Greenland Sea. One float (MZ86) provided tracking information for ten months of the ALS deployment period. The other floats provided tracking information ranging from several days to two months. These float tracks delineated the intermediate depth circulation around the Greenland Sea gyre. The MZ86 trajectory exited the Boreas Basin and crossed the Greenland Fracture Zone with a speed of approximately 17 cm s^{-1}. Along the Greenland continental slope the flow increased to 28 cm s^{-1} suggesting the presence of a bottom trapped boundary current. Near 74°N the trajectory turned eastward under the shallower warm core of the Jan Mayen Current at 4 cm s^{-1}. This leg closed the Greenland Sea gyre and also shows evidence of interactions with filaments of the Norwegian Atlantic Current (NAC) coming through the Mohns Ridge at these intermediate depths. Two other floats demonstrated tracks which crossed the Mohns Ridge and drifted farther to the east, mixing with the waters of the NAC.

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ACKNOWLEDGEMENTS

As with any project of this nature there are many individuals who contribute to its successful completion. Two of particular note are Catherine Rouault of LODYC and Pedro Tsai of the Navy Postgraduate School. Catherine spent much effort in deciphering and answering my many FAX messages as she helped me debug the software by long distance. Pedro offered his assistance in training a UNIX novice into a true UNIX amateur and helped recompile several programs involved in the processing.

A special thanks to my co-advisors, Professors Bourke and Gascard. Professor Gascard made the data and software available to me for this project and provided guidance and careful tutelage from ~3000 miles (~5500 km) away. And Professor Bourke, being my advisor in residence, had the daily task of talking me through problems and most importantly keeping me focused and on track.

To these and my family and friends who helped me through this, thank you.

I. INTRODUCTION

A. OVERVIEW

Fram Strait, the narrow body of water between the east coast of Greenland and the Svalbard Archipelago, has long been recognized as the most important link between the cold polar waters of the Arctic Ocean and the warmer and saltier oceans to the south. On the east side of the strait warm, saline Atlantic Water at the surface is carried northward into Fram Strait and enters the Arctic Basin by flowing under the cold surface waters. To the west, southward flowing currents carry the cold Arctic surface waters and large volumes of ice southward along the eastern coast of Greenland. This results in very large transports of heat, salt, and momentum through Fram Strait. In addition, this exchange contributes to ventilation of the mid-depth and deeper waters of both the Arctic Ocean and the Greenland Sea.

The Greenland Sea is an area where deep convective processes have been observed and is considered to be a major producer of the deep waters found in the more southerly oceans. The overall circulation controls the rate of convection by varying the sensible heat and fresh water to the central gyre. These currents also redistribute the ventilated waters and the other mixing products. Because of its role in ventilating the deep oceans, the Greenland Sea plays an important role in the world climate system by controlling a large part of the global thermohaline circulation. An understanding of the large-scale three dimensional circulation in the Greenland Sea is important to the understanding of the global impact of

changes in the ventilation of the deep water and the thermohaline circulation. (*Rudels et al.*, 1989, *GSP Group*, 1990)

The mean large-scale surface currents of the Greenland Sea are reasonably well understood. Many studies using satellite-tracked floating buoys, satellite ice drift observations and dynamic height calculations have contributed to this knowledge (*Bourke et al.*; 1987, *Johannessen et al.*; 1987, *Quadfasel et al.*; 1987, *Bourke et al.*, 1991). Circulation of the deep currents is not as well understood. Limited knowledge has been gained from some deep current meter moorings (*Muench et al.*, 1986; *Foldvik et al.*, 1988; *Aagaard et al.*, 1991) and some studies with deep drifting buoys (*Gascard et al.*, 1988). These have been limited to the vicinity of Fram Strait and the East Greenland Shelf. Part of the mission of the Greenland Sea Project (GSP) was to gain additional knowledge of the deep currents of the basin (*GSP Group*, 1990). To this end, twelve subsurface floats and four tracking stations were deployed in September 1988 in the vicinity of Fram Strait. Four more floats were launched in April and May 1989 in dynamic features (eddies) in Fram Strait. In August 1989 three additional tracking stations were deployed farther south in the Greenland Sea in order to continue tracking these previously launched floats.

This study examines the trajectories of several of the aforementioned, acoustically-tracked, drifting SOFAR floats as they transitted through the Greenland Sea and around the Greenland Sea Gyre. These floats transmit acoustic signals at scheduled intervals that are received by the stationary tracking stations. The tracking stations record the time the signal was received. A combination of two or more of these received signals are used to determine the float position (*Manley et al.*, 1989). Decoding the data retrieved from the

tracking stations deployed in 1989 and analysis of the float trajectories is the focus of this thesis.

B. BACKGROUND

The Greenland Sea is a semi-enclosed basin delineated to the north by Fram Strait, to the west by the Greenland coast, to the south by the Jan Mayen Fracture Zone, and to the east by Mohns-Knipovich Ridge System. Figure 1 is presented as an overview of the geography of the Greenland Sea. This sea can be further divided into two basins, the Boreas Basin to the north and the Greenland Basin to the south. The two basins are separated by the Greenland Fracture Zone. Both basins have depths in excess of 3000 m. The east Greenland continental shelf makes up a significant portion of the Greenland Sea, extending to the east for over 350 km at depths less than 400 m (*Muench et al.*, 1986). The circulation of the Greenland Sea is dominated by the cyclonic circulation of the Greenland Sea Gyre, which is driven by the wind stress curl (*Johannessen et al.*, 1987).

The West Spitsbergen Current (WSC) carries warm, saline Atlantic Water (AtW) northward on the eastern side of the Greenland Sea (Figure 2). The cold, fresh East Greenland Current (EGC) flows southward on the western side. At the northern margin, in Fram Strait, a portion of the WSC dives beneath the Polar Water (PW) north of Svalbard into the Eurasian Basin. Between 78°N and 81°N a branch of the WSC turns westward across Fram Strait (*Bourke et al.*, 1988) and then turns southward converging with the EGC at the continental shelf break. This flow continues southward as the Return Atlantic Current (RAC) with its

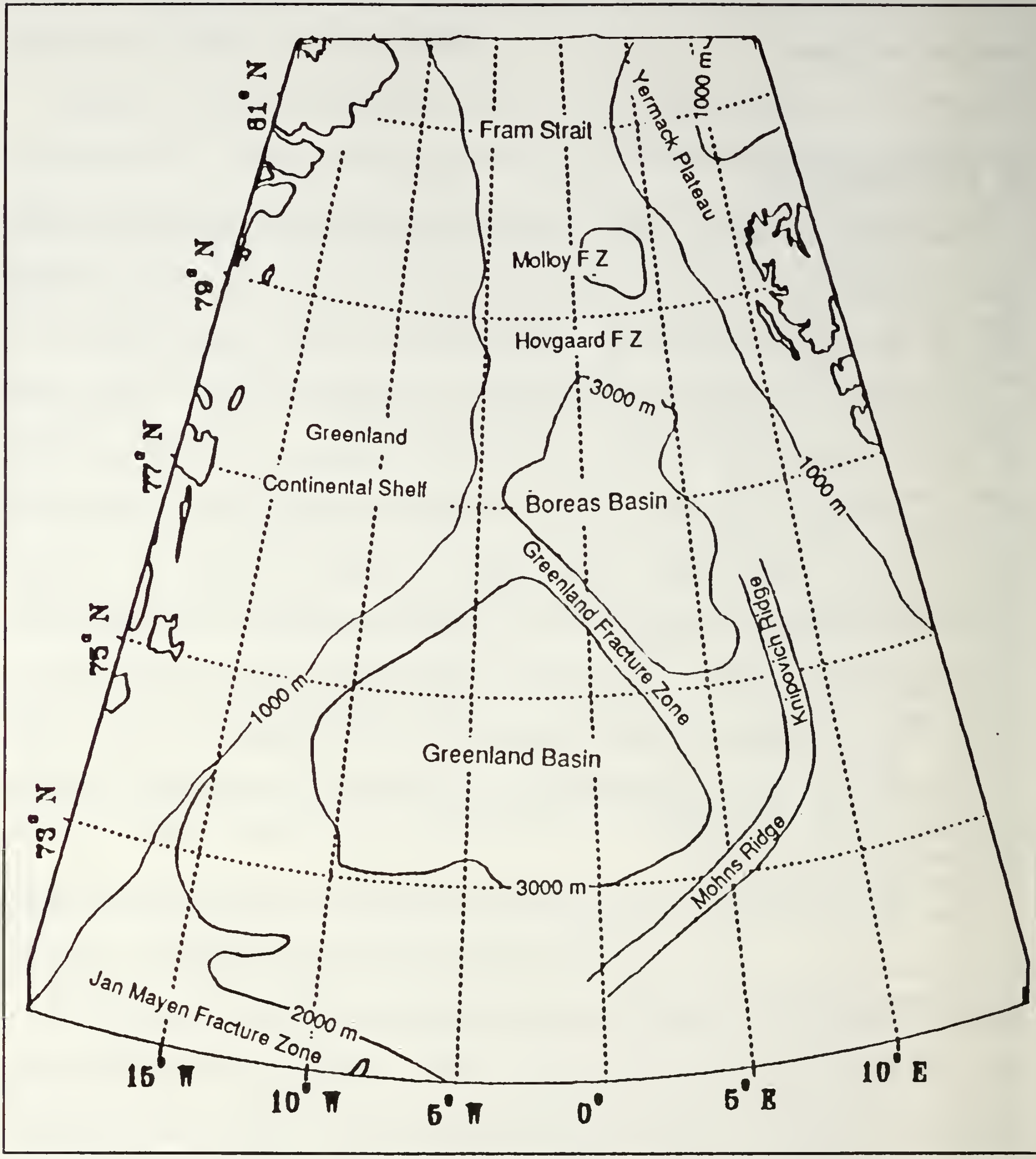

Figure 1. A schematic chart showing the components of the Greenland Sea and Fram Strait bathymetry. The 2000 m isobath is used to delineate the rise of the Jan Mayen Fracture Zone and becomes nearly coincident with the 1000 m contour along the Greenland continental slope. The 3000 m isobath is used to define the center of both the Boreas and Greenland Basins, a generalization of the 2000 m isobath was used to delineate Mohns Ridge.

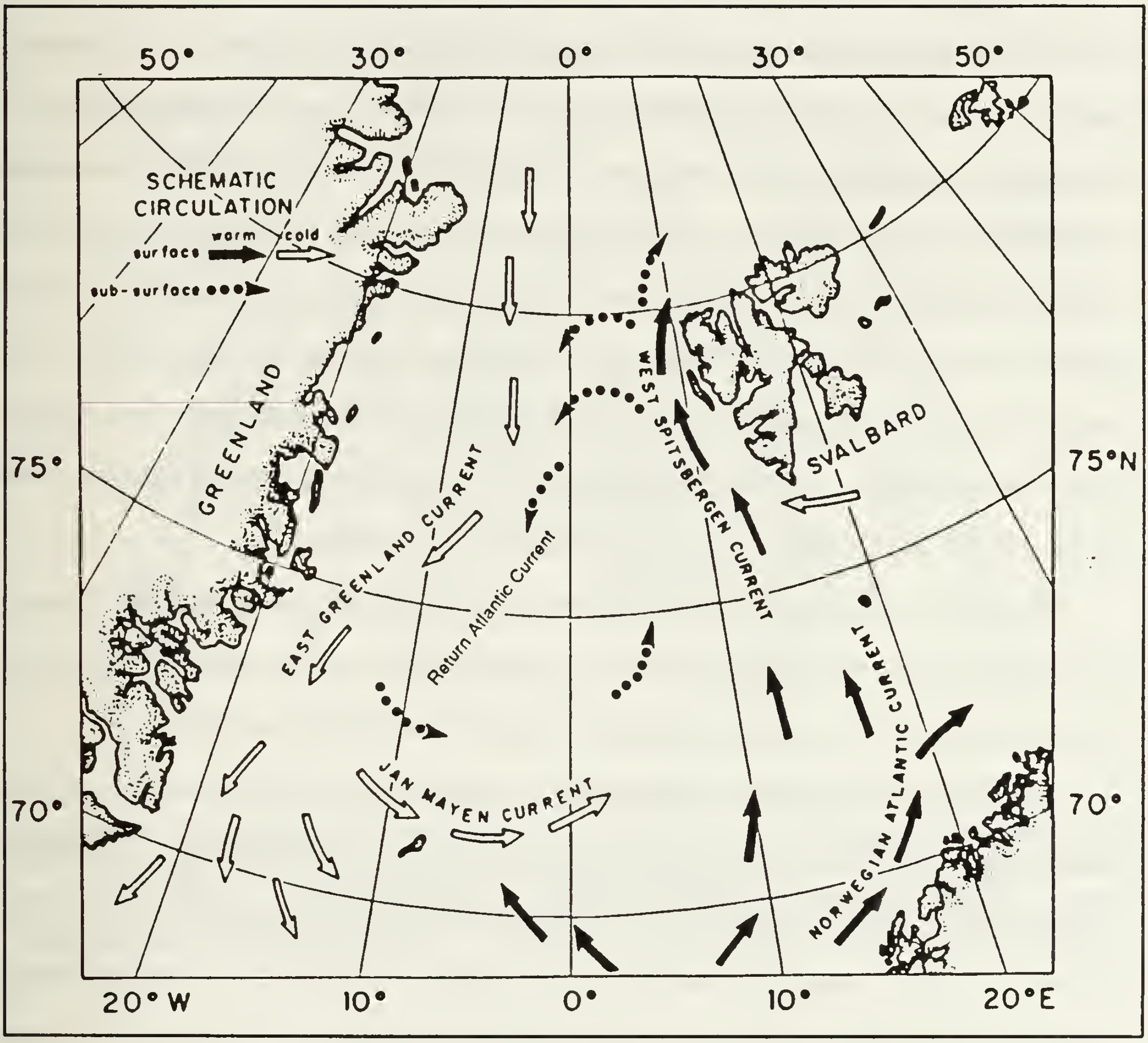

Figure 2. A chart showing the circulation in the Greenland Sea and Fram Strait (modified from *Koltermann and Lüthje,* 1989).

core beneath and seaward of the PW of the EGC. The RAC is separated from the PW of the EGC by the East Greenland Polar Front (EGPF). At the southern edge of the Greenland Sea the Jan Mayen Current (JMC) turns to the east, north of the Jan Mayen Fracture Zone (JMFZ) to close the Greenland Sea Gyre.

The EGC is a broad southward flow originating in the northern reaches of Fram Strait and extending laterally from the Greenland coast to the continental slope. It can be vertically partitioned into two distinct components. The first is the broad, predominantly barotropic, southern flow overlying the Greenland continental shelf and slope. The second part of the EGC is a shallow (~100-200 m) baroclinic near-surface layer. Part of this surface layer is a narrow (~50 km) baroclinically driven jet that generally follows the continental shelf break. The core of the jet is coincident with the EGPF which separates the cold, low salinity water being carried from the Arctic Basin from the warmer, higher salinity water of the central RAC. (*Paquette et al.*, 1985; *Hopkins*, 1988)

The WSC is the northernmost extension of the Gulf Stream Current System. The WSC is driven by the topographic funneling effect of the cyclonic circulation in the Greenland Sea against the Svalbard shelf break (*Morison*, 1991).

The EGC and the WSC come together in Fram Strait. The interaction of these nearly opposing flows causes complex features to develop in the strait. The WSC begins to dive beneath the EGC as it approaches the EGPF near 80°N. The WSC breaks into two separate branches as it enters Fram Strait. The first turns eastward across the continental shelf north of Svalbard. The second turns westward as two flows, a southern limb across the Hovgaard Fracture Zone and a northern limb in the Molloy Fracture Zone and central Fram Strait but limited to

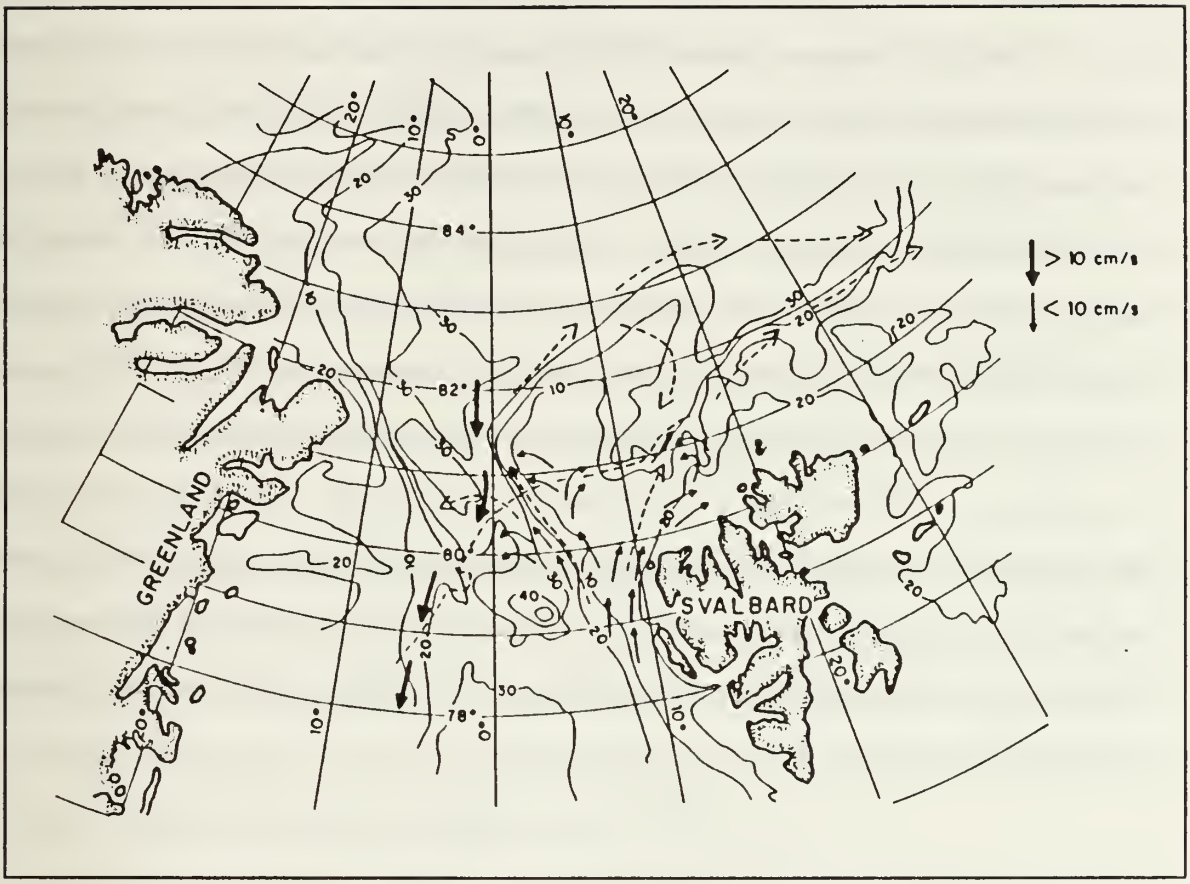

Figure 3. Circulation of the WSC showing both the coastal eastern branch of the WSC and an inferred branch (dashed arrows) following the seaward contours of the Yermak Plateau. The bold arrows indicate speeds greater than 10 cm s^{-1}. Bathymetry in hundreds of meters (from *Perkin and Lewis*, 1984).

the area south of 81°N. Figure 3 shows the characteristic flow in Fram Strait. The westerly branch becomes the Return Atlantic Current (RAC) after crossing the strait and then turning southward along the continental shelf break. (*Bourke et al.*, 1987)

The Jan Mayen Current (JMC) appears at the surface as both a branch of the EGC projecting eastward as the southern limb of the Greenland Gyre and as a meander to the EGC flow (Figure 2) (*Blythe,* 1990). The barotropic flow of the intermediate and deep water continues to the east roughly following the topography of the JMFZ. The JMC is characterized by a near surface tongue of cold and fresh Polar Water (PW) projecting eastward around 73° N. It may also be discerned by the eastward turning of the warm, saline intermediate waters of the RAC at ~100 m depth. This water, termed the Jan Mayen Atlantic Intermediate Water (JMAtIW) by *Hopkins* (1988), is displaced about 75 km north of the PW tongue and can be traced eastward across Mohns Ridge until its ultimate merger with the intermediate water of the Norwegian Atlantic Current (NAC) (*Bourke et al.*, 1991).

C. SOFAR FLOATS

Acoustically-tracked Lagrangian drifting floats have been used with great success in observing the deep currents in the mid-latitudes (*Owens*, 1984). Because of its exploitation of the Deep Sound Channel (DSC), this technology has taken on the name SOFAR from <u>SO</u>und <u>F</u>ixing <u>A</u>nd <u>R</u>anging and refers to floats which transmit an accoustic signal to a moored reveiver. SOFAR floats were originally designed to exploit the long range propagation paths of the DSC; in the Arctic regions this path is not available.

The propagation characteristics in these northern latitude waters are upward refracting at all depths due to the overall positive sound speed gradient found in Arctic waters. This situation is often termed half channel propagation. For long range propagation the half channel path is dependent on multiple surface interactions. Therefore the characteristics of the surface at the reflection nodes are important. Various conditions of under-ice-roughness and surface roughness of the open ocean waters affect the detection ranges of the drifting floats, especially at higher frequencies. Hence the ranges expected using SOFAR floats in the Arctic are not as great as those expected in mid-latitude waters. For floats using 260 Hz acoustic projectors, ranges in the mid-latitudes of 1000-2000 km are not uncommon; expected ranges in the central Arctic are 150 - 350 km (*Manley et al.*, 1989).

SOFAR floats, made of aluminum cylinders or glass spheres which are less compressible than sea water, can be set to drift at a constant depth. A careful pre-launch ballasting procedure is used to define the level at which the float will drift. These floats can be set to signal at predetermined intervals, in this case three times a day at eight hour intervals. (*Manley et al.*, 1989)

Two different listening devices are used to record the arrival time of the float signals. One of these, the autonomous listening station (ALS), receives the acoustic signals and records them on tape. The signals are processed after the ALS has been recovered at the end of the deployment period (*Manley et al.*, 1989). A second device is the Arctic Relay Station (ARS) which receives and records the float signals on board a deep moored instrument and then transmits the signals up a mooring cable to a surface float moored above it. The surface

float then transmits the data to a shore station via the ARGOS data relay system. (*Manley et al.*, 1989)

In both cases post processing analysis is necessary to extract the time of arrival (TOA) data for a particular float as received by two or more listening stations. The floats are programmed to transmit their acoustic signals on a predetermined schedule; hence by comparing the TOA's from different stations, spherical geometry techniques can be used to locate the float (*Manley et al.*, 1989). This technique is similar to electronic navigation methods such as those used in LORAN. The in-situ trajectories are plotted from the individual float positions.

D. ARCTEMIZ

The ARCTEMIZ program, sponsored by the Centre National de la Recherche Scientifique and the Instituit Francais de Recherche pour l'Exporation de le Mer (IFREMER), and also a component of the Greenland Sea Project, involved a substantial effort to launch and monitor SOFAR floats in and around Fram Strait (*Manley et al.*, 1989). Twelve SOFAR floats were launched in Fram Strait during the summer of 1988. Eight of these floats were employed to investigate the flow of the intermediate depth Atlantic Water and so were set for medium depths of 300 to 400 m. Four were set to depths of 1000 to 1100 m to examine the behavior of the Deep Water. To monitor the trajectories of these twelve floats three ALSs were deployed in northern Fram Strait. This northern ALS array was retrieved one year later in the summer of 1989. Three additional ALSs were deployed farther to the south in the Greenland Basin in September 1989. It was anticipated that the floats launched in the previous year could be redetected and

tracked through the Greenland Sea and around the gyre. Four additional floats were also launched in the spring of 1989 into eddy-like features in Fram Strait. The southern ALSs were retrieved in August 1990.

Plots of the raw data from the southern ALS array showed the arrival of acoustic signals from three floats launched in Fram Strait in 1988. Two of the four floats deployed in 1989 were also tracked. One of these was tracked over a 10 month period.

E. PURPOSE

The purpose of this study is to examine the data acquired by the three ALSs deployed in the Greenland Sea from September 1989 to August 1990. Adequate data records were available for five floats to be studied. The trajectories derived from the acoustically-tracked floats are analyzed with regard to their mean and eddy motion, and the relationship to known fronts, currents and bathymetric features.

II. DATA

The SOFAR float data consist of the recorded time of arrivals (TOA) of the float signals as received at an ALS. By using the TOA from three ALSs for a given float, the instantaneous float position and the drift of the float's internal clock can be estimated using simple spherical geometry and a nonlinear least squares fit (*Manley et al.*, 1989). Processing software from the Laboratoire D'Oceanographie Dynamiques et de Climatologie (LODYC), Paris, has been modified for use in this study and is described below.

As part of the ARCTEMIZ project, twelve SOFAR floats and three ALSs were deployed in Fram Strait in August - September 1988 west of Spitsbergen. The intent was to examine the circulation of the intermediate and deep waters in Fram Strait. The initial launch position of each float and the mooring positions of the 1988 ALSs are illustrated in Figure 4. Table 1 provides the details of these deployments.

The ALSs were recovered in 1989 and the data processed by Laboratoire D'Oceanographic Dynamique et de Climatologie (*Gascard*, 1990). Three of the 1988 floats (AR48, AR50, and AR57) were still trackable a year later by the 1989 ALSs. As an aid to their later analysis, their trajectories during 1988 are shown in Figure 5.

In 1989 three ALSs were deployed in an attempt to regain contact with the floats launched in 1988. The mooring locations for these ALSs were designed to allow adequate tracking of the presupposed float drift paths and to ensure reasonable mooring depths. One ALS was moored on the shallow rise of the Greenland Fracture Zone and two on shallow depth spurs of the Jan Mayen

Fracture Zone. Four additional intermediate depth (200 m) floats were launched into eddy-like features in Fram Strait during April and May 1989. One float MZ86 was specially ballasted to initially settle at 200 m then settle at 1 m per day until reaching 500 m and then remaining at that depth. The 1989 deployment locations of the ALSs and floats are shown in Table 2 and Figure 6. Only the float trajectories tracked by the 1989 ALSs are analyzed in this study.

TABLE 1. DETAILS OF 1988 FLOAT AND ALS DEPLOYMENTS

Float #	Depth	LAT	LON	Launch
46	1000 m	79 27.8N	5 29.7E	8/29/88
47	1000 m	78 00.3N	2 51.2E	9/6/88
48	1065 m	78 45.2N	4 56.7E	9/4/88
49	1055 m	78 44.7N	1 27.8E	9/5/88
50	340 m	77 15.0N	10 29.0E	9/6/88
51	300 m	78 01.8N	8 45.7E	8/22/88
52	340 m	79 30.7N	8 05.3E	9/3/88
53	315 m	79 29.0N	6 32.6E	8/29/88
54	320 m	79 00.0N	6 29.0E	8/29/88
55	330 m	79 00.4N	7 24.1E	8/28/88
56	345 m	76 44.9N	12 00.9E	9/7/88
57	335 m	78 29.2N	8 19.5E	8/21/88

ALS #	Depth	LAT	LON	Launch	Recover
7	900 m	75 05.0N	1 49.6E	8/16/88	8/19/89
11	714 m	80 06.4N	4 34.9E	8/30/88	9/2/89
18	817 m	80 48.3N	12 56.3E	8/31/88	9/3/89

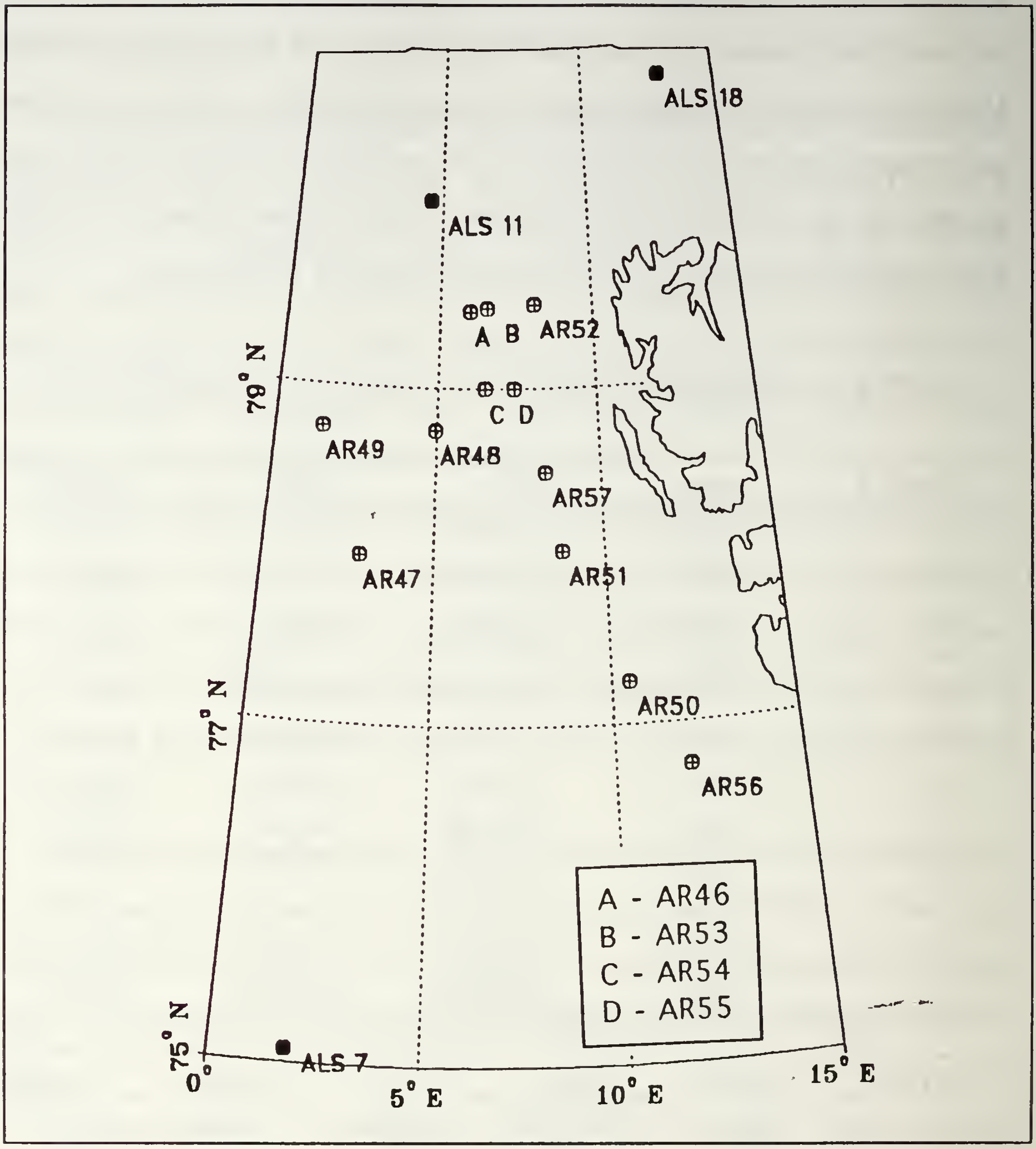

Figure 4. 1988 ALS (solid dots) and float deployment locations.

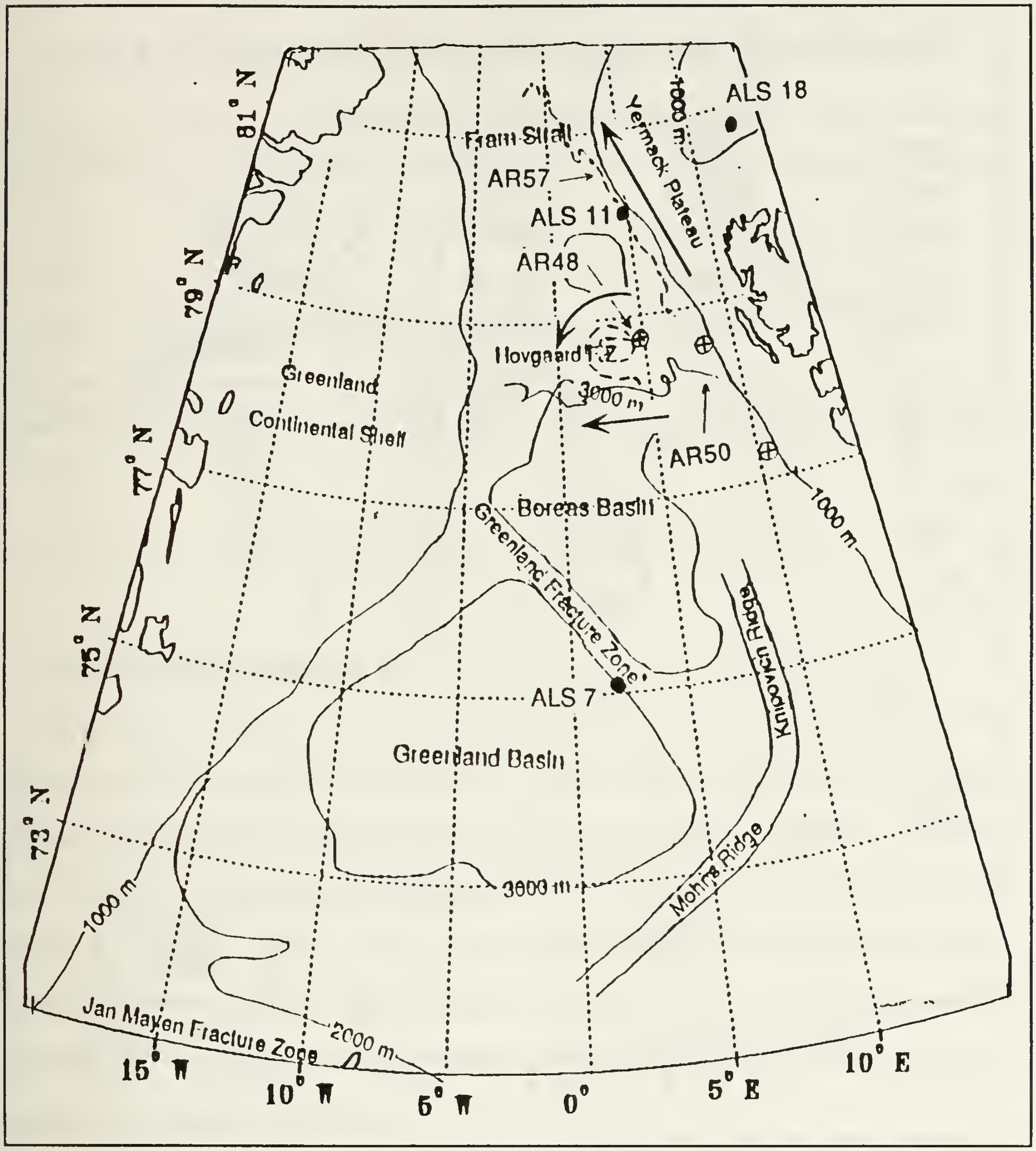

Figure 5. 1988 Trajectories of floats AR48, AR50, and AR57. The launch positions of the floats are indicated by circles.

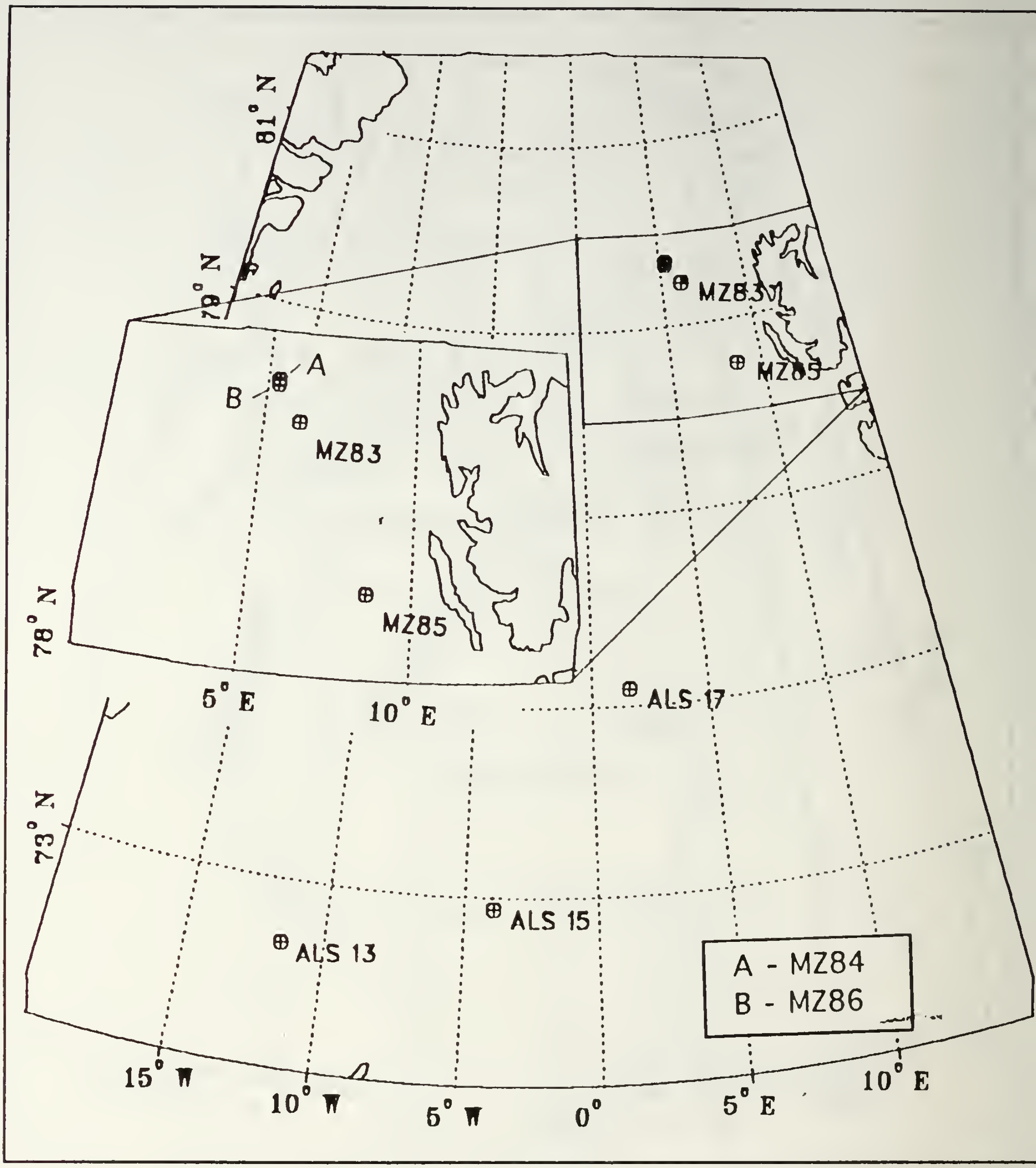

Figure 6.   1989 ALS and float deployment locations.

TABLE 2. DETAILS OF 1989 FLOAT AND ALS DEPLOYMENTS

Float #	Depth	LAT	LON	Launch
83	200 m	79 28.2N	6 10.8E	4/14/89
84	200 m	79 42.7N	5 22.2E	4/14/89
85	200 m	78 30.7N	8 38.5E	5/17/89
86	200-500 m	79 40.9N	5 21.6E	4/14/89

ALS #	Depth	LAT	LON	Launch	Recover
13	700 m	72 20.9N	11 33.7W	9/14/89	8/10/90
15	740 m	72 53.2N	3 54.2W	9/19/89	8/16/90
17	757 m	75 11.5N	1 37.3E	9/9/89	8/5/90

A. DATA PROCESSING

Raw plots of the 1989 ALS data, showing signal strength versus time, indicated that three floats launched in 1988 (AR48, AR50, and AR57) had adequate information to allow tracking during the 1989 deployment. The raw data also showed strong signals from two floats deployed in the spring of 1989, MZ83 and MZ86. Figure 7 is a sample record typical of these raw data plots. This plot shows received signals from four floats. A plot of the floats tracked showing the time periods of the tracking during the entire 1989 ALS deployment period is provided in Figure 8.

The raw ALS data, i.e., the recorded time of arrival of the float signal at an ALS, was processed using software provided by LODYC. The processing is accomplished in three steps using seven programs. In the first step additional data files are created which are used in later processing. In the second step each

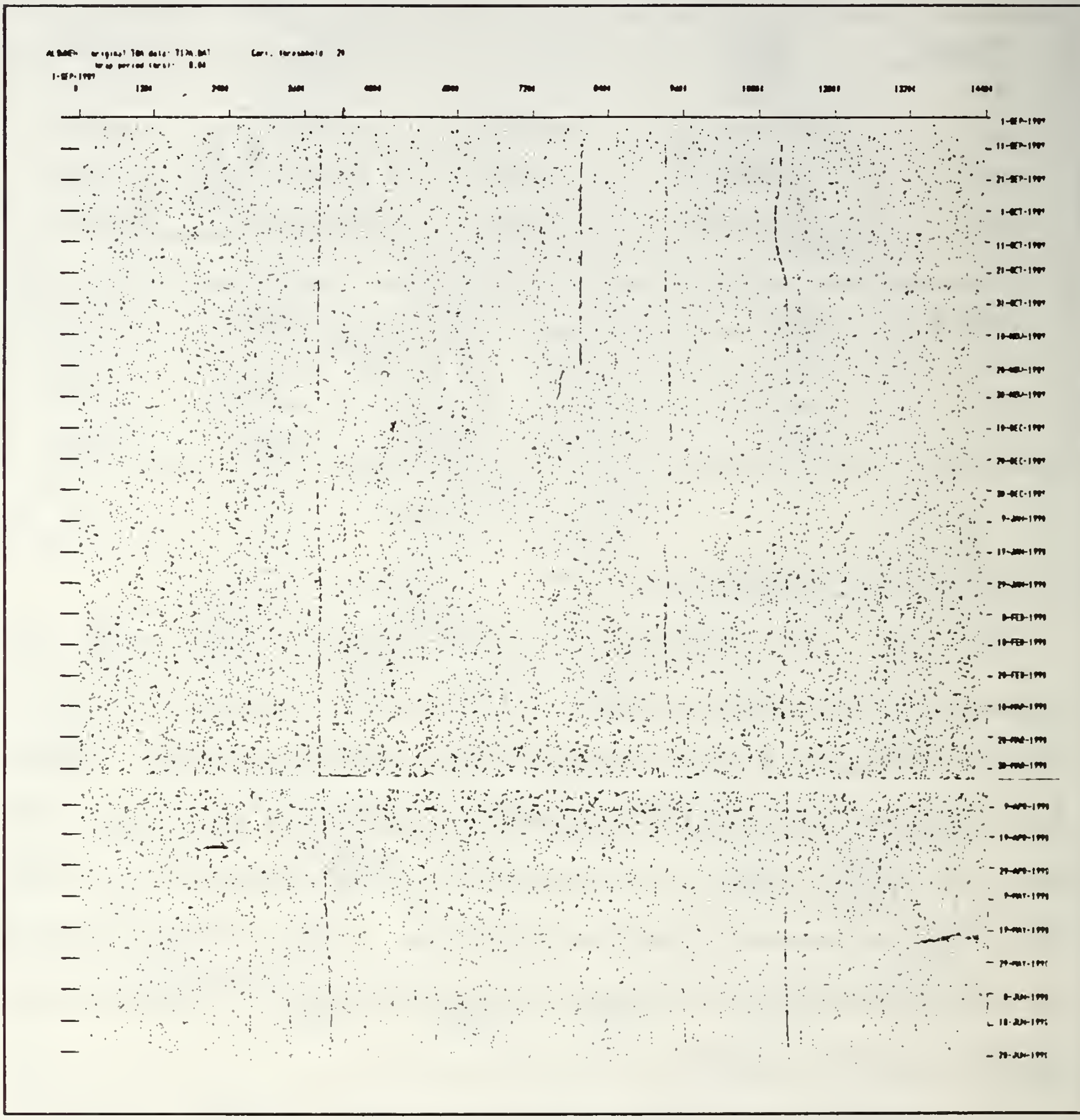

Figure 7. Waterfall display of the ALS raw data, signal versus time. This plot shows signals from four different floats.

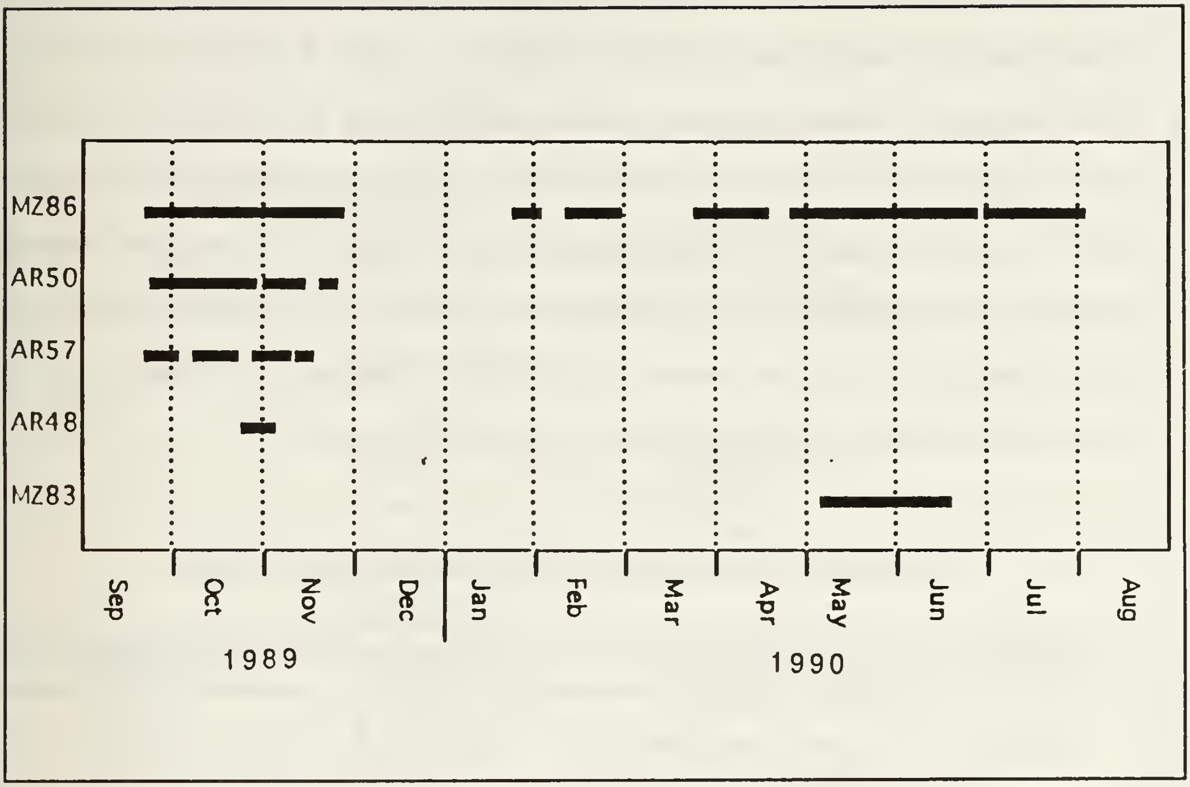

Figure 8. Bar chart showing time periods each float was tracked during the 1989 ALS deployment.

ALS data file is treated separately, extracting the signal of a particular float and interpolating to fill short data gaps. Step three brings together the data from three ALSs to calculate the clock drift for the float and ultimately calculate its position. A flow chart of a sample run is shown in Figure 9. Table 3 provides an overview of the programs. These programs were initially written by LODYC to run on a SUN 3 workstation. With one exception, the programs were recompiled to run on a SUN 4 workstation at the Naval Postgraduate School The program **mansig** could not be recompiled; one of its subroutines, **curses**, is machine specific to the SUN 3 and could not be converted to the SUN 4. The program **mansig** was run on a SUN 3 courtesy of the Computer Sciences Department.

TABLE 3. PROGRAM FUNCTIONS AND FILES.

Program	Description	files created	files used
alsentry	used to create data files for ALS and float deployment info	.FLT .ALS	none
mansig	extracts data for a specific float from the raw ALS data	.TOA	.FLT .ALS .data
flterp	interpolates .TOA file to fill data gaps	.INT	.TOA
flind	calculates float clock drift	.CLK	.FLT, .ALS. .INT
clkdrft	writes the calculated float clock drift to the .FLT file	none	.CLK, .FLT
flind	calculates float positions	.POS	DIRINT.DAT, .INT, .FLT, .ALS
toflt	formats the final position file	.PRI	.POS

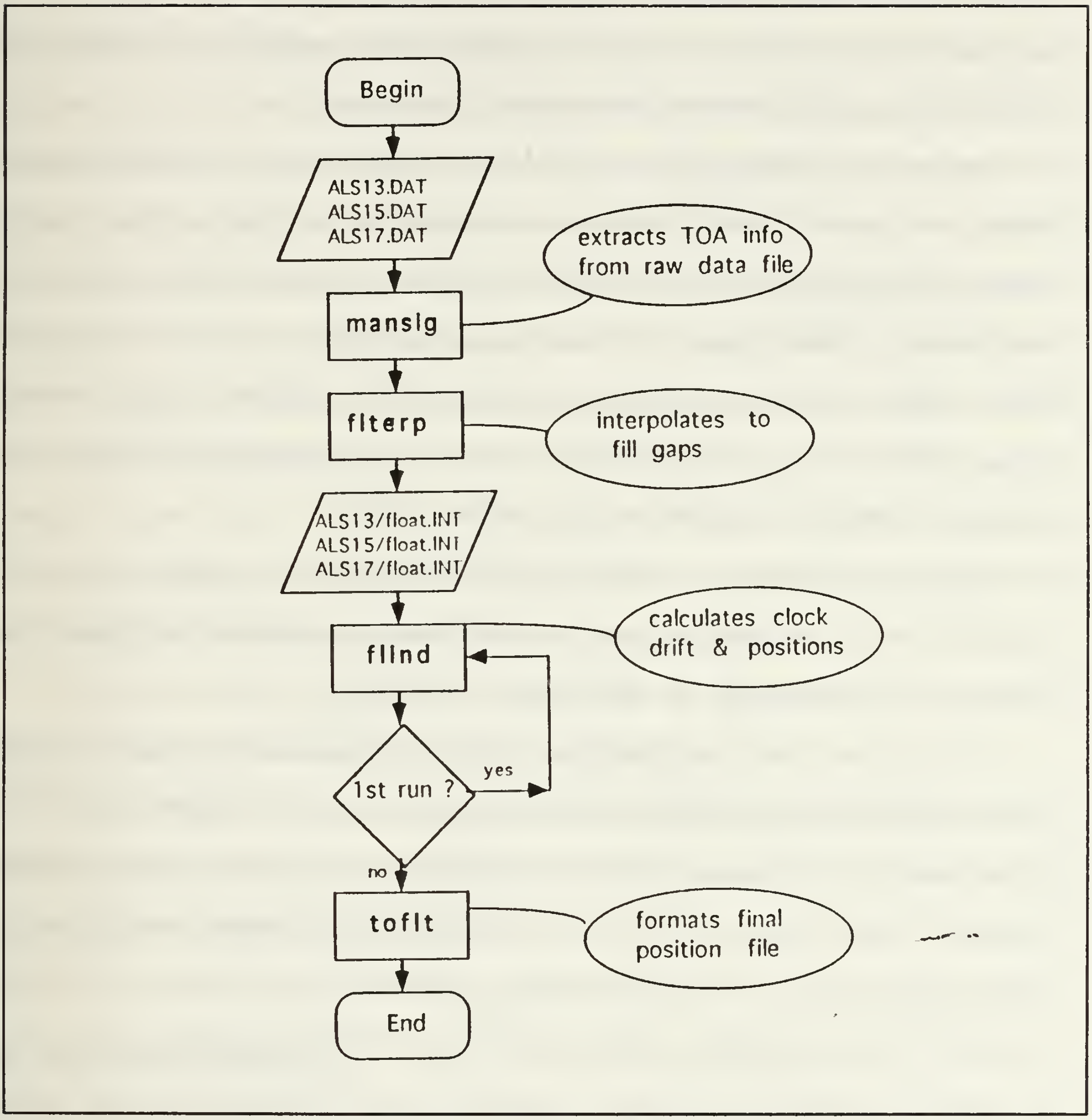

Figure 9. Processing flow chart.

The program **alsentry** creates two data files used in later processing. These files contain information on the deployment characteristics of each float and each ALS. Files with the suffix of .ALS contain the location, date of deployment, depth, and measured internal clock drift information for each ALS. The files with a .FLT suffix contain the same information for each float.

The program **mansig** applies the ALS clock drift to the raw ALS data and tracks the signal of each float as received by the ALS. This program automatically tracks the received signals based on an allowable time differential between consecutive signals. If more than one signal is received in the allotted time window, the operator must select between the available signals. **Mansig** outputs a file of time of arrivals (TOAs) for the signal of each float as received by each ALS. This file is identified with the suffix of .TOA.

The program **flterp** checks the .TOA file for possible bad points, asks the user to approve each questionable point and does a linear interpolation of all gaps less than 5 days. **Flterp** creates an interpolated (.INT) file.

The program **flind** calculates the drift of the float's internal clock and the incremental positions of the float. **Flind** needs an input file DIRINT.DAT. This file, created in an editor, is a list of the .INT files used in determining the float positions. **Flind** must be run twice; the first run is to compute the drift of the float's internal clock. The program **clkdrft** applies this clock drift to the .FLT file for use in later processing. The second run of **flind** determines the float incremental positions using the calculated clock drift for the float. Since distances are related to TOA by the mean sound speed along the path, a typical sound speed is required. **Flind** uses a default sound speed of 1.495 km sec^{-1}. However, assuming a mean temperature of 2° C and a mean salinity of 34.8 PSU,

a value of 1.46 km sec^{-1} was selected as being more representative of the actual conditions in the deployment area.

A float position is computed within **flind** by using the first two arrival times to establish an initial area of probability from the intersections of distance arcs from two ALS mooring positions. The distances are determined by multiplying the time difference between the TOA at the ALS and the scheduled float transmit time by the estimated speed of sound. For two distance arcs there are two possible solutions, one on each side of the ALS baseline. The resolution of this position ambiguity is done by using a third distance arc from another ALS, if available, or by choosing the intersection closest to the last good fix. A quasi-Newtonian fit is then applied to minimize the sum of the least squares error from the calculated position to each ALS. If the rms error is greater than 10 km, then low quality TOAs are excluded and the minimization continues. The output of this program is a raw position file with the suffix .POS file. (*Gascard*, 1990)

The last program **toflt** converts the .POS file of raw positions into the final output positions in latitude and longitude, a .PRI file.

The positions were then smoothed in latitude and longitude, using an IMSL cubic spline error detection (CSSED) scheme. A sample plot of raw data and smoothed data is provided in Figure 10.

B. PROGRAM ERRORS

The initial runs for float MZ86 showed an improbable trajectory with the float drifting onto the Greenland continental shelf in waters < 300 m and through Shannon Island (Figure 11). It was obvious that this was not a realistic solution. A detailed review of the processing procedure was done, comparing runs using

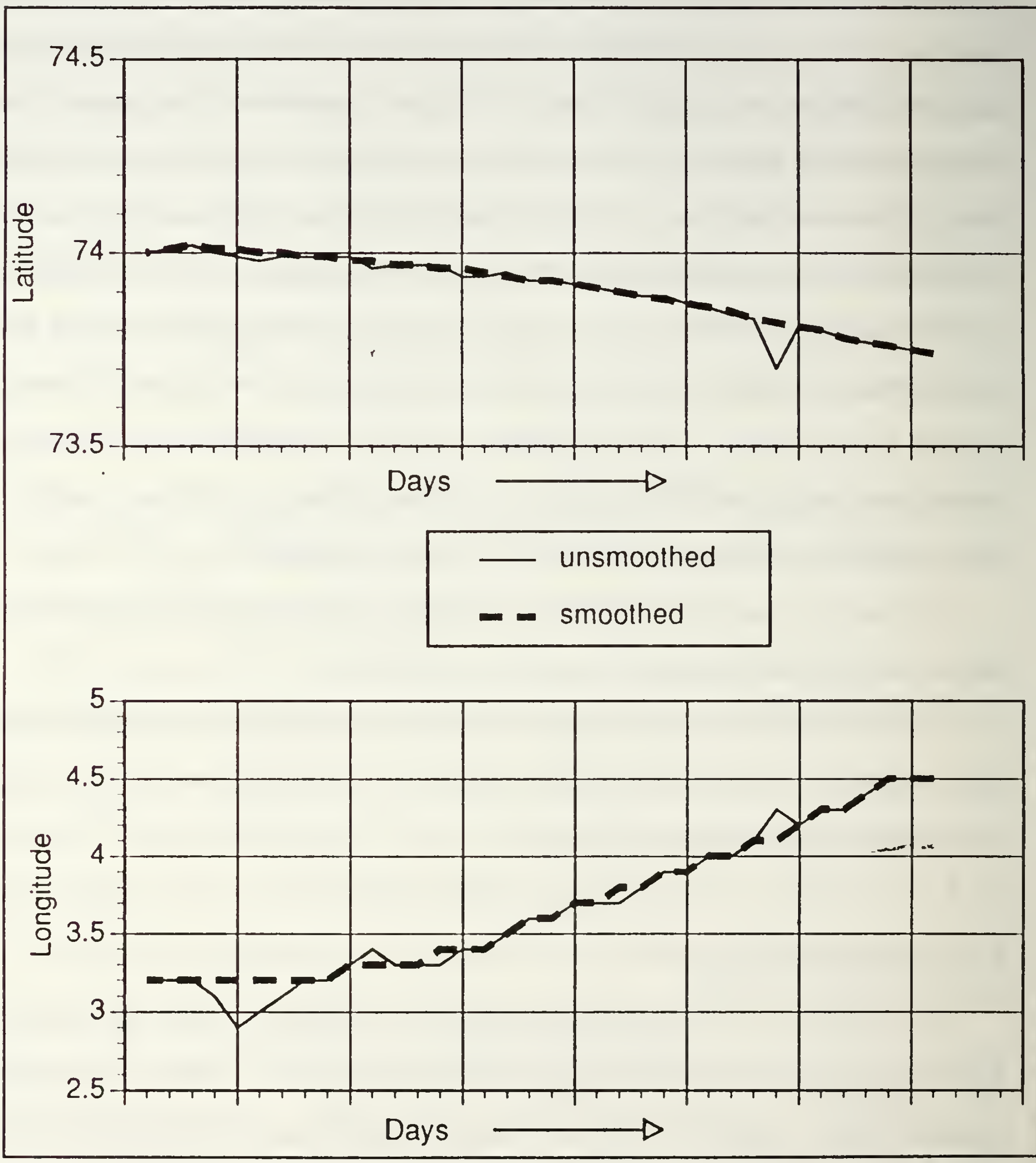

Figure 10. Results of cubic spline smoothing.

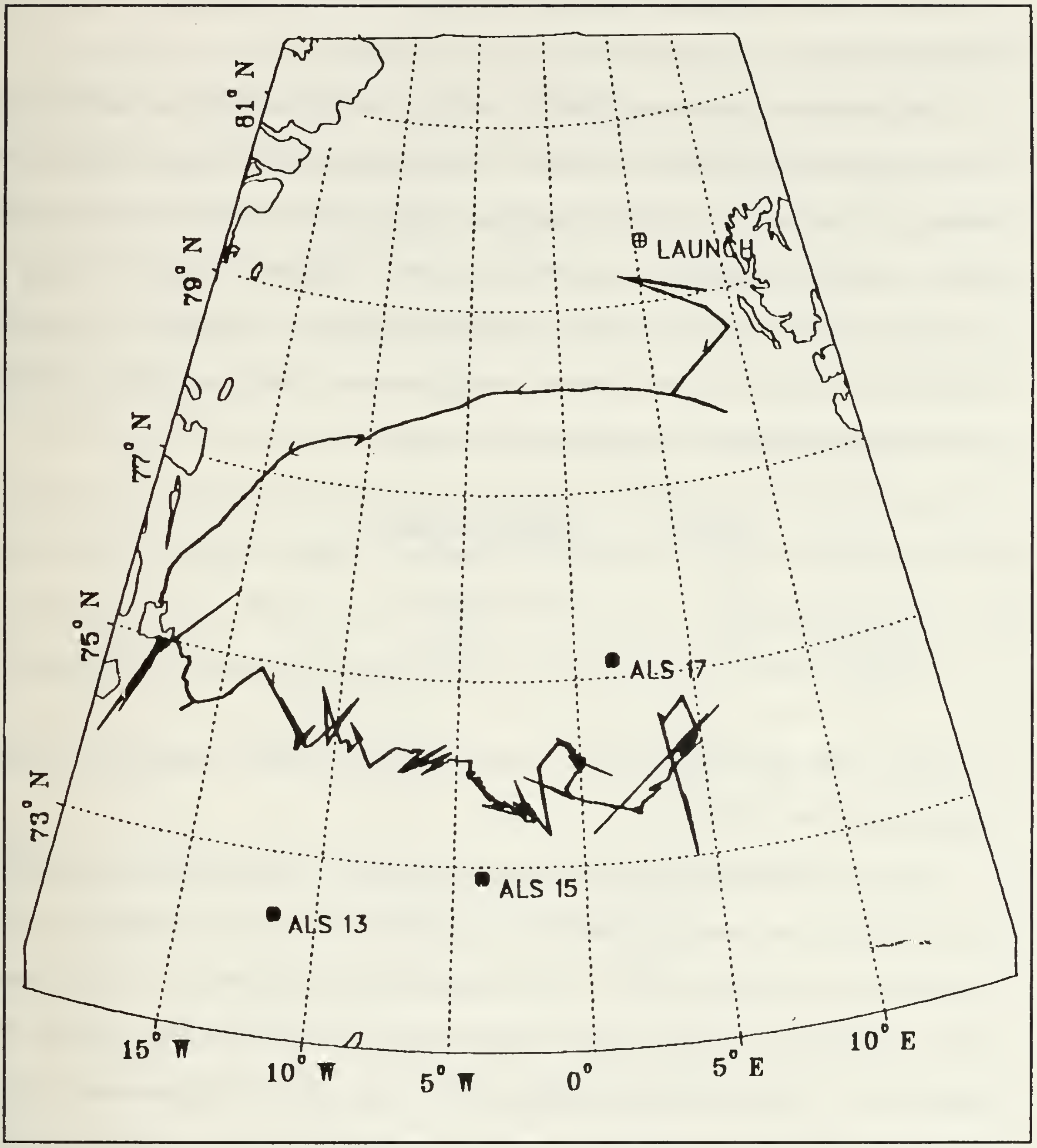

Figure 11. Plot of float MZ86 with the improperly applied ALS 17 clock drift.

different parameters in a search for a clue to the error which could cause this bad tracking. It was ultimately tied to improperly applying the ALS clock drift as described below.

The position calculation in **flind** is based on the TOA of the float signal at the ALS. Both the float and the ALSs have internal clocks which may be subject to drifting, in some cases appreciably during a year's deployment. Hence, the clock drift of each float and ALS must be determined. The clock drift of the ALS is measured when it is recovered and is applied linearly through the program **mansig** to the raw TOA file when extracting the data. The three 1989 ALSs had the following clock drifts over their deployments :

ALS	clock drift (secs)
13	+0.58
15	-5.15
17	-153.5

As can be seen, the drift for ALS 17 was more than 2 orders of magnitude greater than the other two ALSs.

Two runs of **mansig** were performed on the ALS 17 data against float MZ86. One run was done using the measured clock drift for ALS 17; another run was done using a zero clock drift. It was expected that these two runs would have TOAs differing by the clock drift applied linearly over the duration of ALS 17's deployment. TOAs in early October (one month into the deployment) were expected to differ by only about 13 seconds but were found to be different by 65 seconds. Realizing that MZ86 was deployed in April 1989 and that ALS 17 was

deployed in September 1989, 5 months apart, it was apparent that five months at 13 seconds per month resulted in a drift error of 65 seconds.

From this it was determined that the program **mansig** was applying the ALS clock drift, not from the beginning of the ALS deployment as required, but from the beginning of the float deployment. In this case, with the float deployed five months prior to the ALS deployment and ALS 17 having such a large clock drift, a large error in TOA resulted. For the 1988 floats deployed a full year prior to deployment of ALS 17 the accumulated error of the clock drifts at the end of the ALS deployment would be on the order of three minutes.

To correct for this error **mansig** was rerun to extract the TOA information for each float against each ALS with the ALS clock drift set to zero. A program was then written to properly apply the clock drift to the .TOA file for the deployment period of the ALS. Figure 12 is a plot of MZ86 with this correction applied. All subsequent processing then continued as before using this corrected data file.

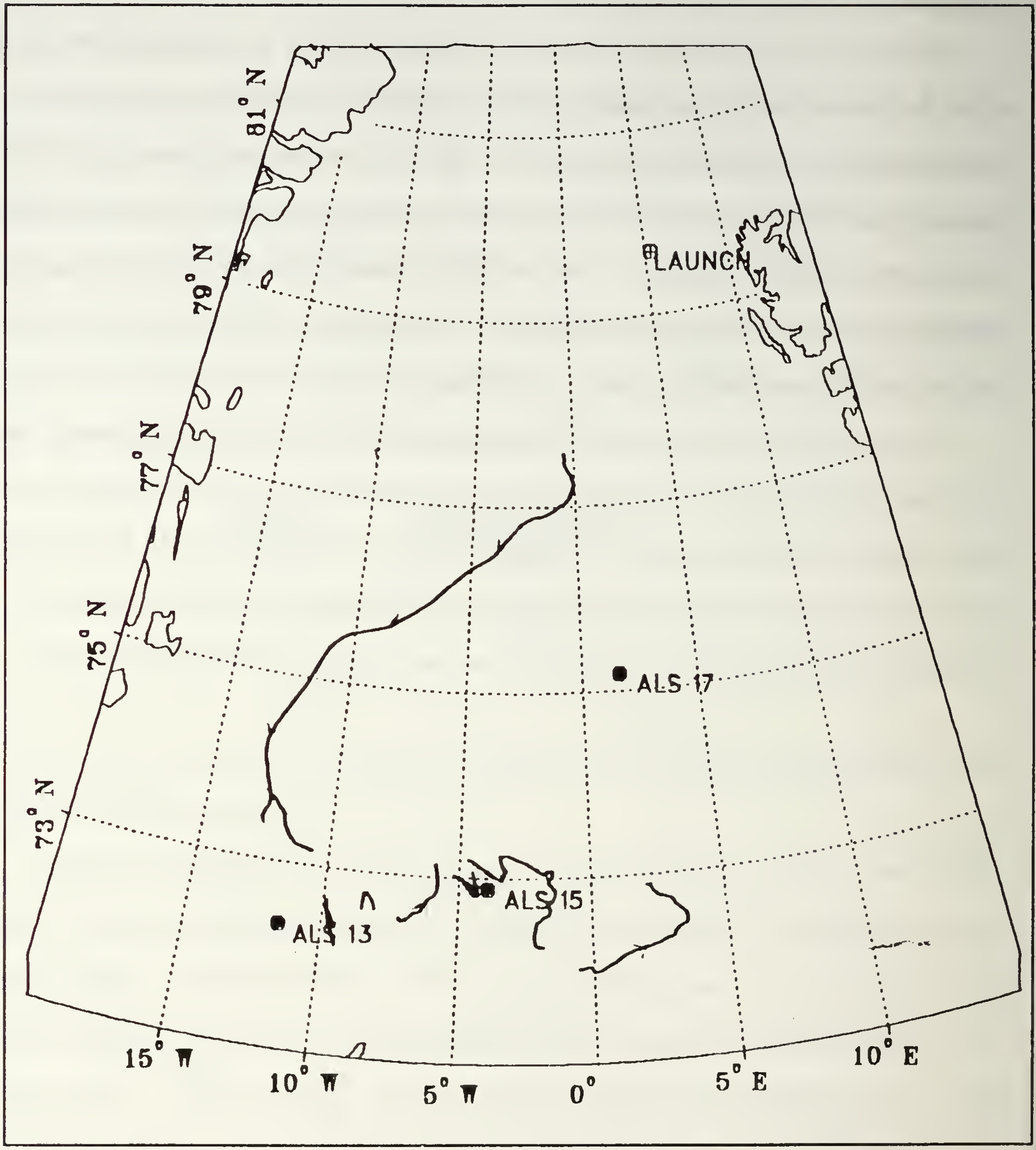

Figure 12. Plot of float MZ86 with the ALS 17 clock drift applied correctly.

III. RESULTS

Plots of the raw 1989 ALS data indicated that signals from five floats had adequate signal strength and record length to provide useful tracking. Three of the twelve floats launched in Fram Strait in 1988 were tracked during the period from September to November 1990. Two of the four MZ floats launched in the spring of 1989 were tracked, one for over ten months while the other float tracked for a short period in the spring of 1990. The tracking results are summarized in Table 4.

TABLE 4. DURATION OF FLOATS TRACKED DURING 1989 BY THE SOUTHERN ALS ARRAY.

Float	Begin Tracking	Lose Tracking	Duration (days)
MZ86	27 Sept 89	4 Aug 90	312
AR50	24 Sept 89	25 Nov 89	62
AR57	22 Sept 89	19 Nov 89	58
AR48	26 Oct 89	1 Nov 89	5
MZ83	9 May 90	3 Jun 90	28

A. MZ86

Float MZ86 was launched on 14 May 1989 into the waters of the WSC over the continental shelf break off the west coast of Spitsbergen. This float was tracked for a longer period of time and with a better signal strength than any other float examined in this study. It was tracked from late September 1989

through August 1990 but with several short breaks in the record possibly due to topographic blockage of the signal. A plot of the entire track along with its hypothesized track in summer 1989, prior to its acquisition five months later, is shown in Figure 13. The hypothesized track, shown as a dotted line, is based on a previous analysis of the drift pattern of SOFAR floats launched and tracked in this area during the MIZEX 84 experiment (*Gascard et al.*, 1988). Figure 14 suggests two possible drift paths, one to the northwest along the western margin of the Yermack Plateau and one to the west or southwest through the complex series of eddies associated with the Molloy Fracture Zone. The track to the northwest was chosen because of the similar placement of MZ86 to AR57 relative to the Spitsbergen continental shelf. The proposed track is an approximation to the track taken by AR57. A speed of 3.6 cm s^{-1} would be required for the float to follow the proposed track of Figure 13.

The horizontal velocities between each position suggest three different current regimes as shown in Figure 15 and summarized in Table 5. These individual regimes are shown in Figure 13 as legs 1, 2, and 3.

TABLE 5. DETAILS OF THE INDIVIDUAL MZ86 TRACKING LEGS.

Leg	Start	End	Avg. Speed
1	27 Sep 89	9 Oct 89	17 cm s^{-1}
2	10 Oct 89	25 Oct 89	28 cm s^{-1}
3	26 Oct 89	3 Aug 90	3-5 cm s^{-1}

MZ86 was tracked in late September moving south through the center of the Boreas Basin, shown in Figure 13 as leg 1, with an average velocity of 17 cm s^{-1}.

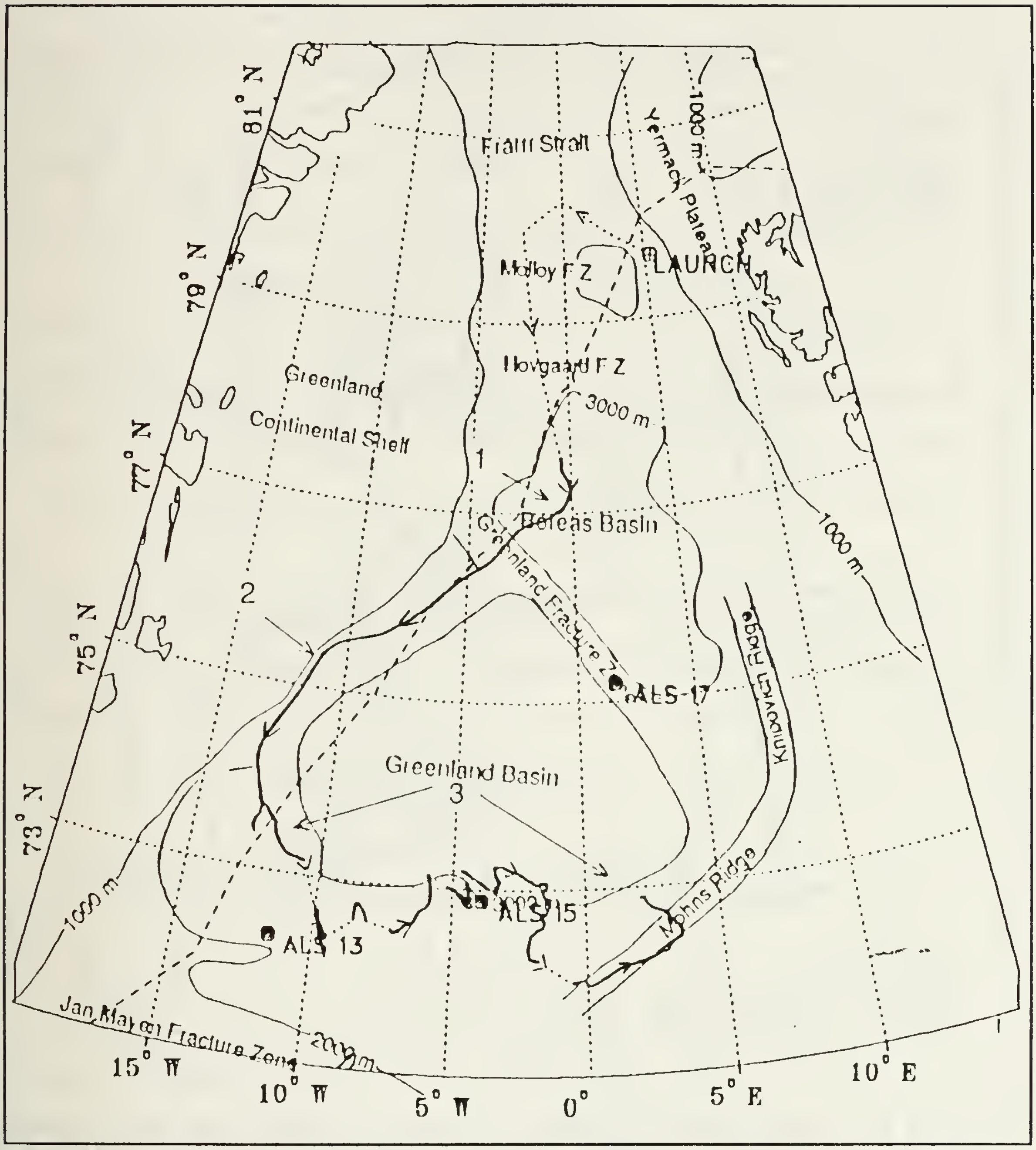

Figure 13. Trajectory of float MZ86. The dotted line represents an estimated track between launch and the beginning of tracking; the dashed line is the approximate position of the ice edge during 1-30 October 1990.

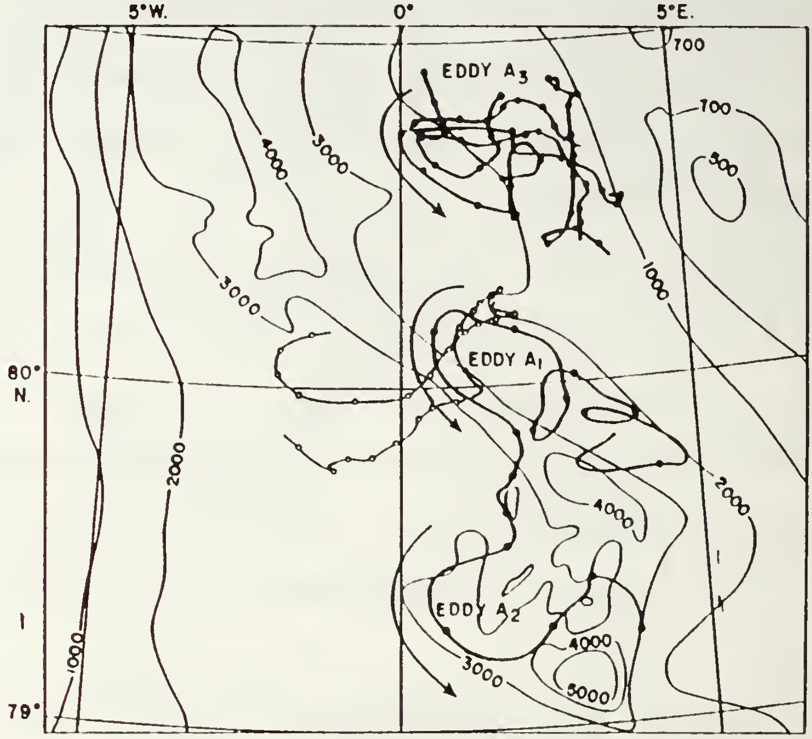

Figure 14. Two SOFAR float drift tracks during MIZEX 84. Dots represent positions every other day. Open circles represent the track of a MIZEX 83 surface drifter (from *Gascard et al.*, 1988).

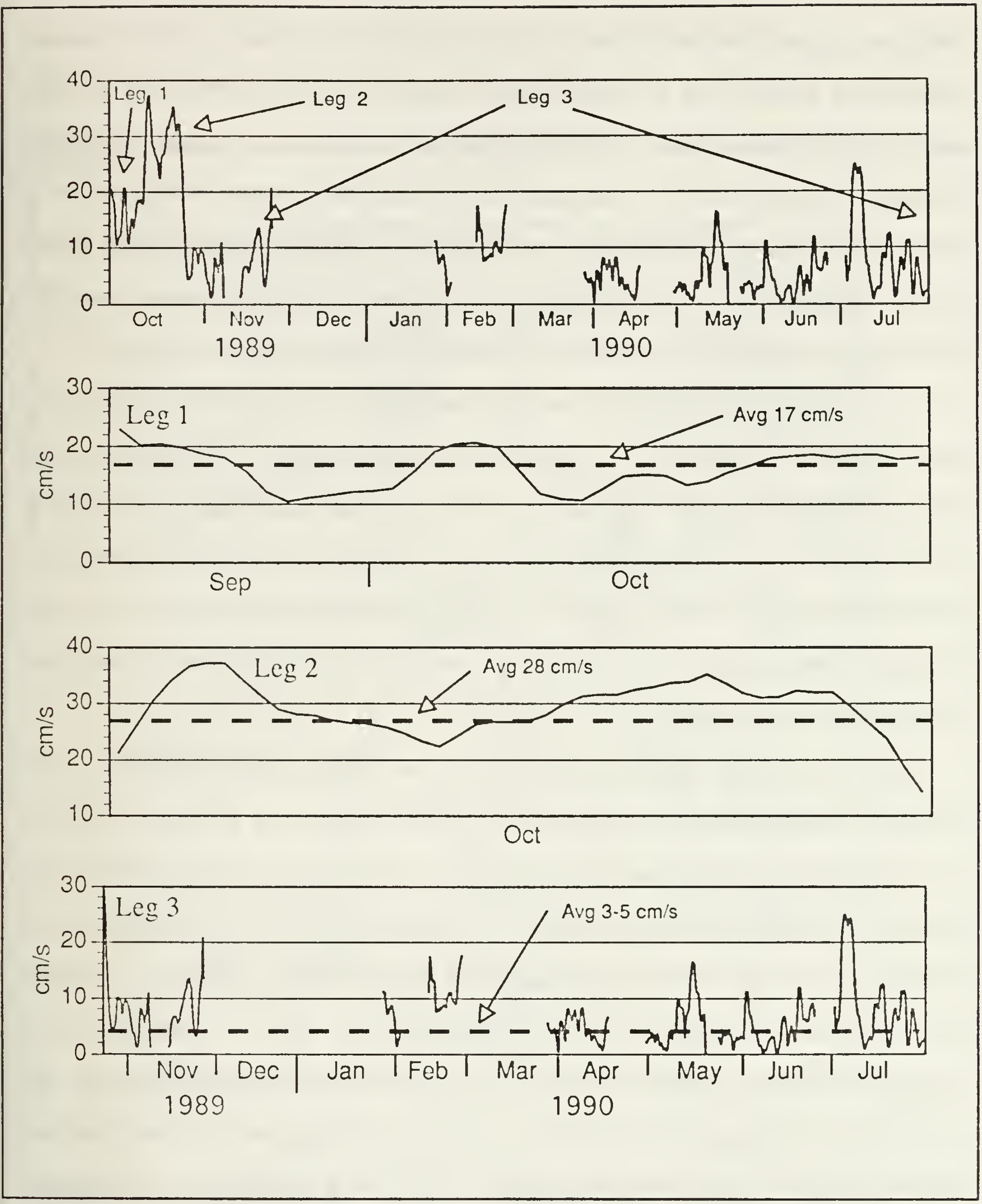

Figure 15. Velocity series for MZ86 from 27 September 1989 to 3 August 1990. Top panel shows overall track while the lower panels show the speeds during legs 1, 2, and 3, respectively.

This speed agrees well with that of *Muench et al.* (1986) who reported current velocities of 10 to 15 cm s^{-1} from current meters at 420 m depth in the western margin of the Boreas Basin. The float continued southwest across the Greenland Fracture Zone and onto the continental slope. The *GSP Group* (1989) reported a satellite-tracked buoy, drogued at 30 m, on almost an identical track (Figure 16) as part of MIZEX '87. This suggests that the near-surface currents and the intermediate currents in this area are coupled as far as direction is concerned.

As MZ86 approached the Greenland continental shelf at about 76.8°N, its speed increased to 28 cm s^{-1} and followed the margin of the Greenland Continental Shelf (leg 2). It continued along the shelf break but upon reaching 75.5°N tracked more southerly. *Bourke et al.* (1987) showed that currents over the Greenland shelf break in this region can reach speeds of 34 cm s^{-1}. These currents, related to the baroclinic EGC jet, were found to be limited to the upper 150 m as shown in Figure 17.

MZ86 was below this layer of baroclinic flow at approximately 400 m. The baroclinic contribution to the flow at 400 m was found to be less than 2 cm s^{-1} from Figure 17. The remaining 26 cm s^{-1} of the flow must be due to the barotropic component which is accelerated in this region by its interaction with the continental slope. This acceleration may be explained as follows. The deep flow along the continental slope is analogous to the flow in a channel on a rotating plane (*Gill,* 1982). The flow is enhanced by the balance between the Coriolis force and potential vorticity. A slope of isopycnal surfaces near the bottom indicates a baroclinic component to the flow approaching the bottom with the higher density surfaces to the right. If the width of the flow is comparable in scale to the Rossby radius of deformation, then Kelvin waves may

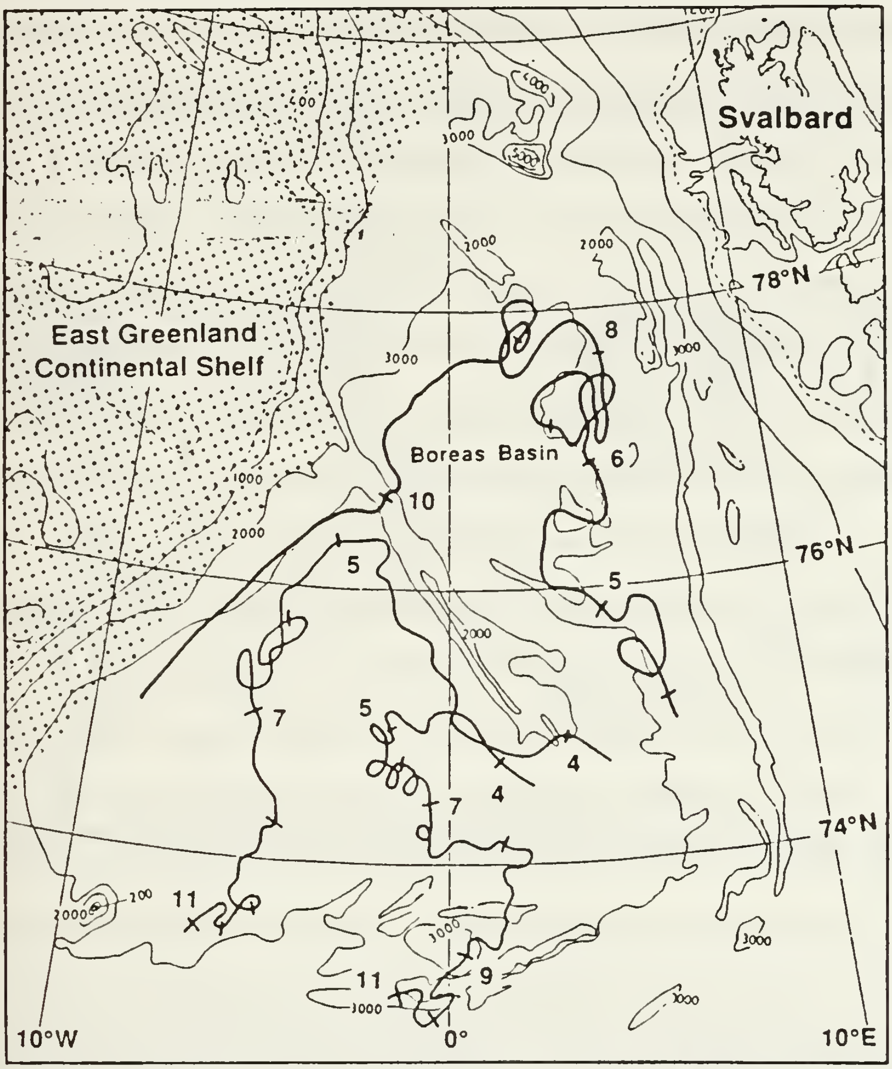

Figure 16. Trajectory of satellite tracked buoys (drogue at 30 m) from MIZEX '87 (numbers indicate date of position) (from *GSP Group*, 1989).

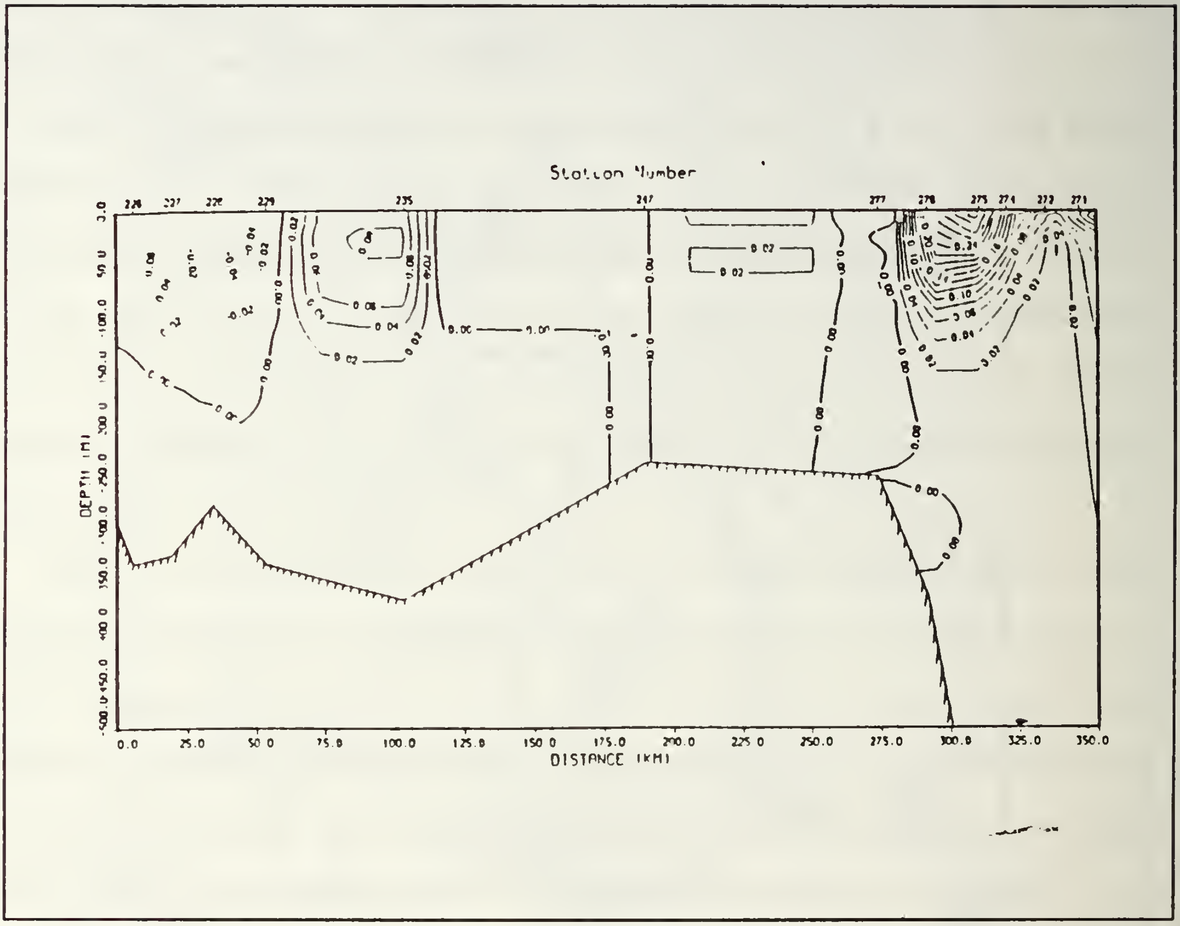

Figure 17. Vertical baroclinic current velocity section at 77.5°N (contours are in m s^{-1}). The jet of the EGPF centered over the upper continental slope indicates speeds of up to 34 m s^{-1} (from *Bourke et al.*, 1987).

be set up traveling along the flow with the slope/boundary to the right. Aagaard (1990) described similar enhanced slope-trapped currents from current meter observations in the Arctic Basin, along the slope northeast of Svalbard. A cross section through one of these features at ~40°E illustrates the presence of a high speed boundary layer current aligned with the continental slope (Figure 18). A similar boundary current was found by *Smith* (1976) at the southern limit of the EGC where it exits over the sill of the Denmark Strait. Figure 19 depicts this boundary current flow as the wedge of dense water from 200 m to the bottom with the isopycnals sloping down to the right, indicating a current out of the paper toward the reader. In this figure the surface manifestation of the EGC is shown as the wedge of lighter water at the surface on the western edge, with isopycnals sloping up to the right, again indicating flow out of the paper toward the reader. *Smith* (1976) found currents on the order of 60 cm s^{-1} near the bottom, suggesting the observed barotropic velocities of 26 cm s^{-1} near 400 m are reasonable. A similar feature was observed in the Meteor 82 data (*Koltermann and Lüthje*, 1989) taken farther to the north which demonstrates a similar convergence of the deep dense water up against the continental slope.

At 74°N the float began a slow turn to the east. The flow of the EGC in this region has been described in the past, most recently by *Aagaard et al.* (1991), to diverge with one component turning eastward at about 74°N and another component continuing south along the slope. The eastward component appears to be derived mostly from waters near the seaward or eastern margin of the EGC while the water closer to the slope continues to the south across the JMFZ. After turning eastward MZ86 meandered across the southern margin of the Greenland Sea (leg 3) with an average velocity of 3-5 cm s^{-1}. During this leg the float was

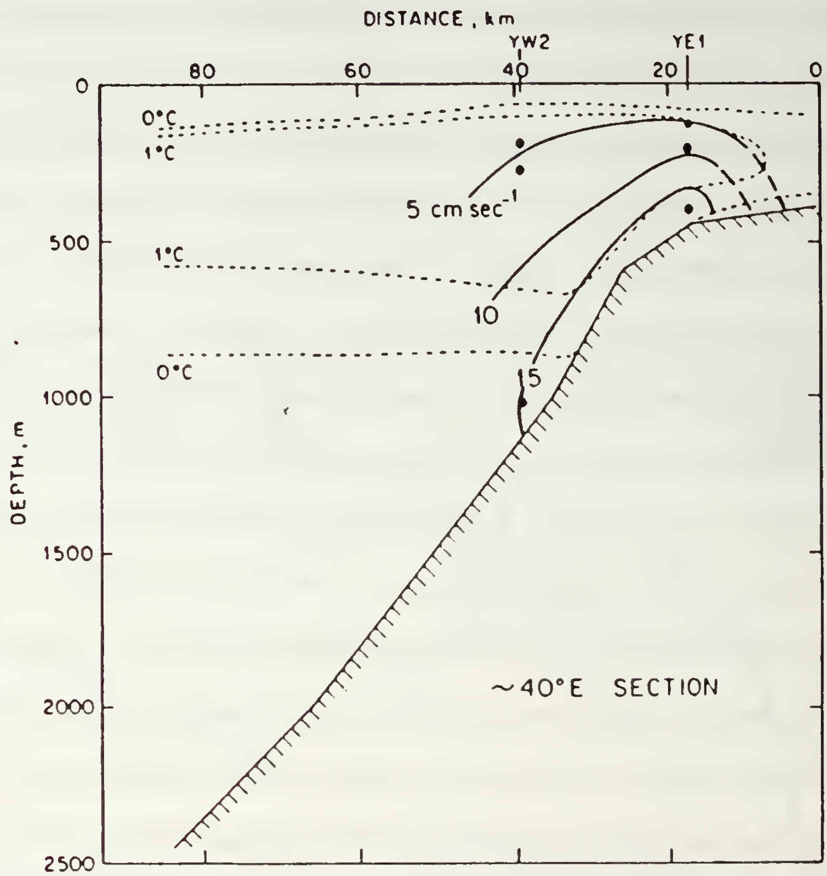

Figure 18. Section across the continental slope in the Arctic Basin showing an intensified boundary current trapped along the continental slope with the velocity increasing toward the bottom (from *Aagaard*, 1989).

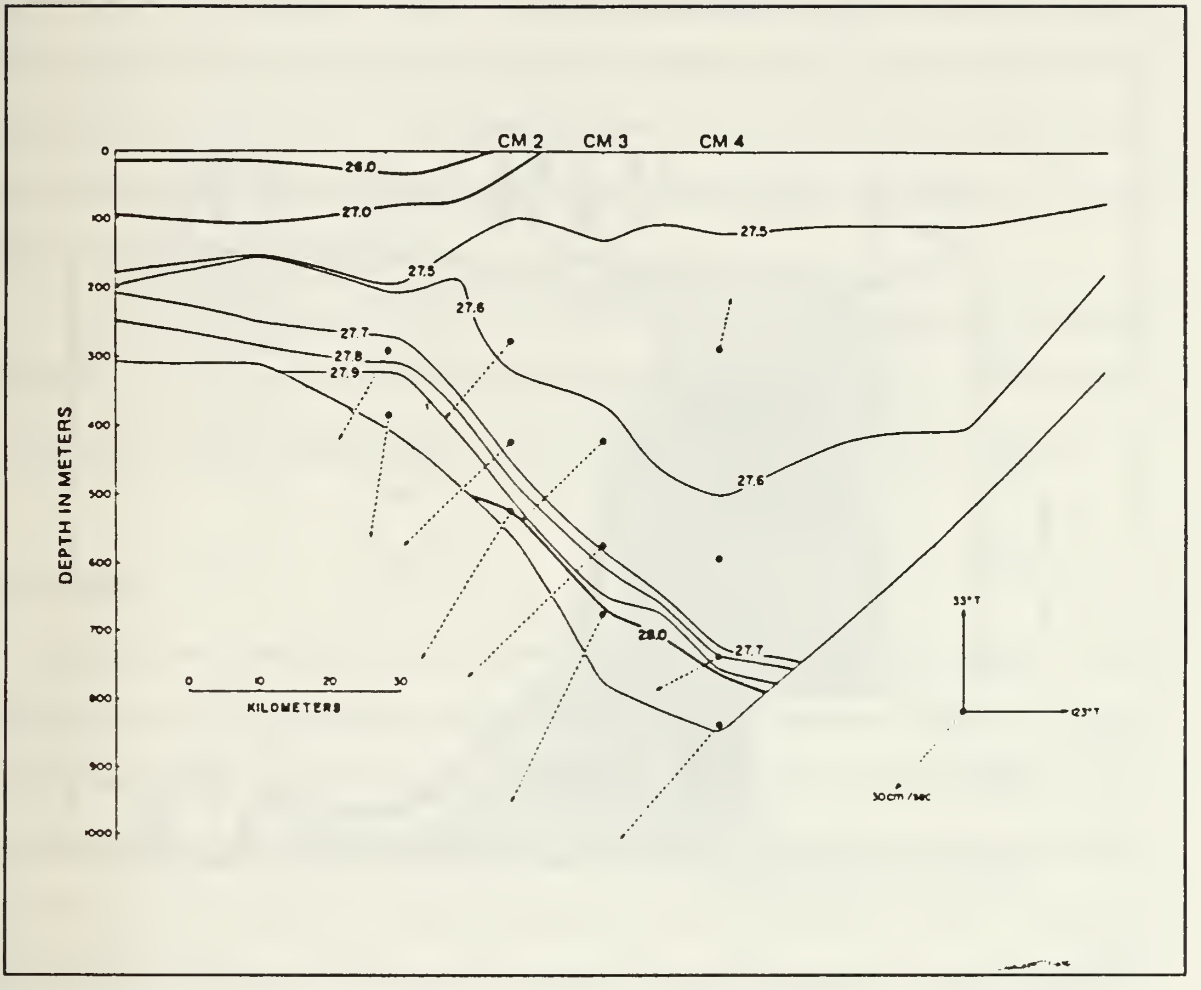

Figure 19. Vertical density (σ_t) cross section across the Denmark Strait (from *Smith*, 1976). Dotted arrows show that measured currents near bottom are directed to the southwest and that they are accelerated as the current is forced against the continental slope.

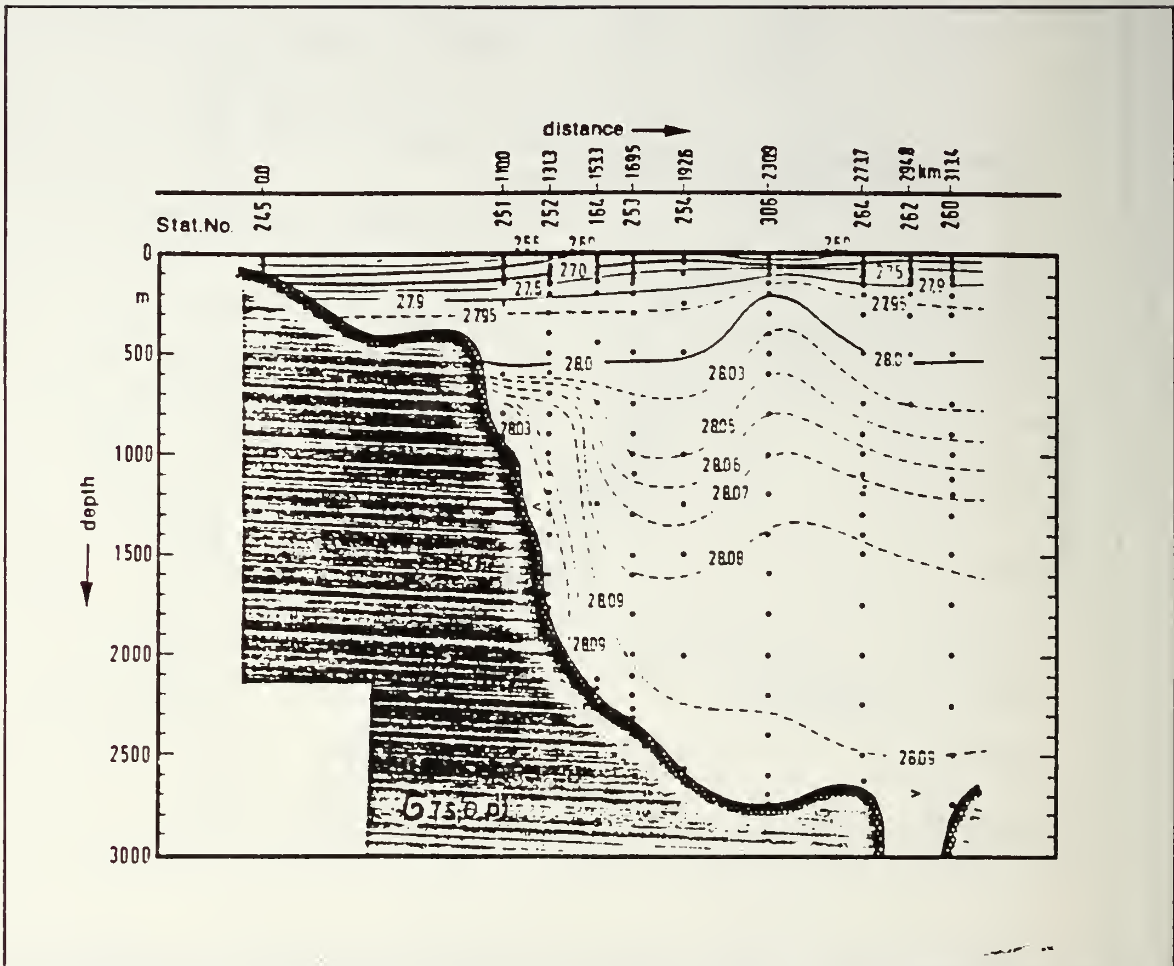

Figure 20. Cross section at 79°N showing the density structure associated with the southward flowing bottom boundary current against the continental slope (from Koltermann and Lüthje, 1989).

embedded in the intermediate waters of the Jan Mayen Current and maximum speeds of more than 20 cm s^{-1} were observed. These values compare closely with observations taken from year-long (1987-1988) moored current meters (*Aagaard et al.*, 1991) which showed mean velocities of 5.5 cm s^{-1} at 93° T at 220 m depth. The position of these curent meters was very close to leg 3 and had an observed maximum of 20.1 cm s^{-1}. An important aspect of their data was that the velocity changed very little with depth (<0.5 cm s^{-1} over 2500 m) indicating the strong barotropic nature of this flow.

During this easterly drift the float was caught up in various eddy-like features. It continued to the east where at 72.5°N it turned to the northeast, apparently merging with a branch of the Norwegian Atlantic Current (NAC).

B. AR50

AR50 was launched on 6 September 1988 south of Fram Strait. It was tracked from 17 September to 13 November 1988 moving west across the Boreas Basin just north of 78°N (Figure 21). Contact was lost with the float near the western edge of the Boreas Basin and it remained untracked until the fall of 1989, when it was located in the southeastern part of the Greenland Sea. A possible drift path, to account for its motion during the nearly one year it was not tracked, may be deduced from the trajectory of MZ86 shown by the dotted line in Figure 21. Considering the distance involved and the time the float was not tracked an average speed of 3.8 cm s^{-1} would be required for the float to navigate this path. On 24 September 1989 contact was gained on AR50 in an area southeast of the Mohns Ridge by the southern ALS array inserted earlier in the month. It tracked northwest more or less parallel to the MZ86 track in the same area in July 1990.

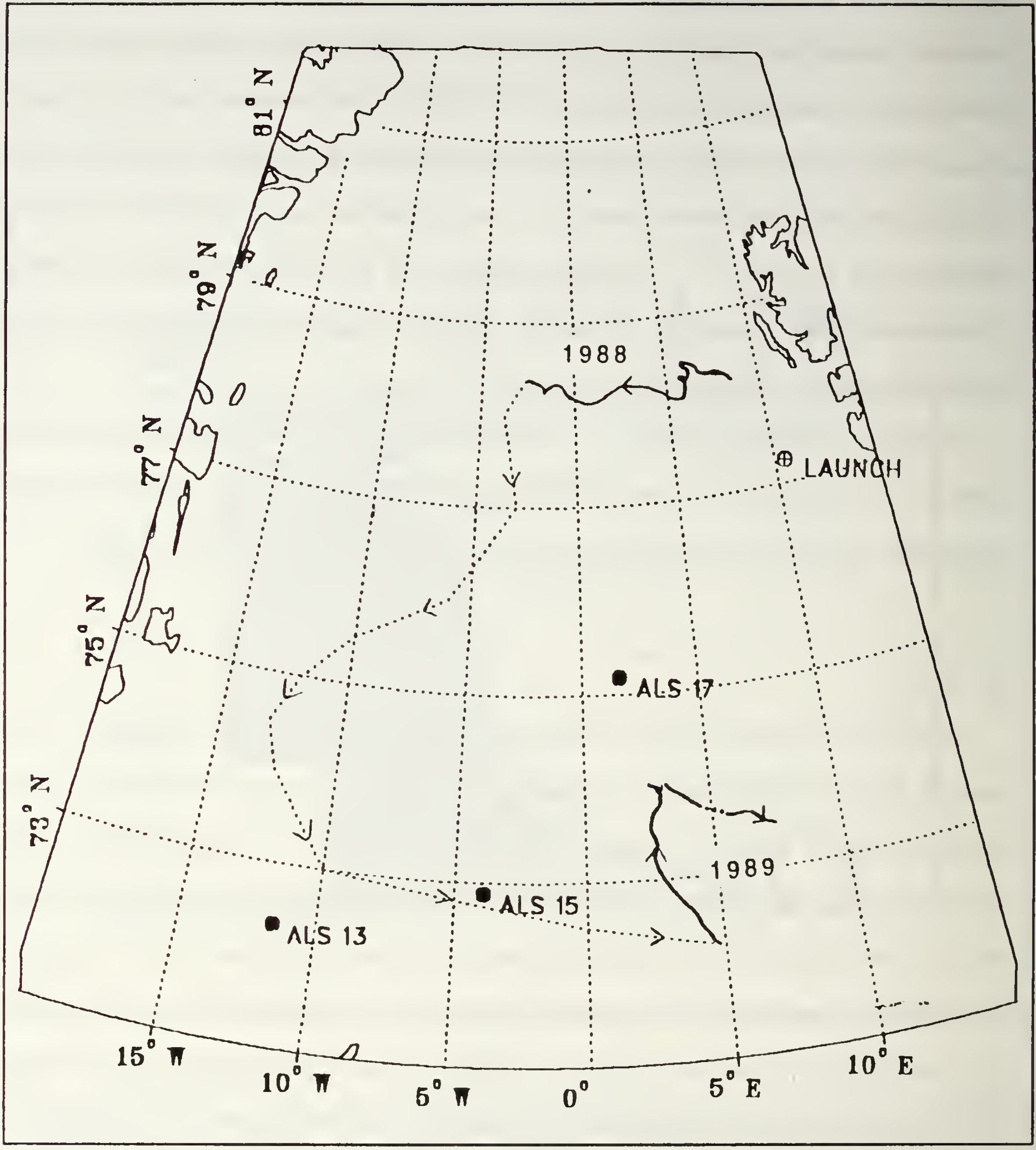

Figure 21. 1988 and 1989 trajectories of float AR50. The dotted line represents an estimated track based on the trajectory of float MZ86.

It then turned back to the southeast and recrossed Mohns Ridge where it was lost again. The path of AR50 appears almost as an extension of the MZ86 track, probably caught in a filament of the Norwegian Atlantic Current.

C. AR57

AR57 was launched on 21 August 1988 into the waters of the WSC. It was tracked by the northern array of ALS's from 30 August to 6 December 1988 drifting to the northwest through Fram Strait and along the Yermack Plateau shelf break as shown in Figure 22. Contact was lost at approximately 81.3°N as the trajectory turned to the southwest. It remained untracked until 22 September 1989. Again, based on the MZ86 trajectory, an estimated track was made to cover the untracked period. An average velocity of 6.2 cm s^{-1} would be necessary to achieve this track. Contact was regained with the float east of Mohns Ridge. Several short tracking periods showed the float moving into the Bear Island Trough of the Barents Sea north of Norway. The nature of these short tracking periods suggests that the signal was blocked by the high relief of Mohns Ridge, with occasional periods when the float was positioned such that the signal passed through the breaks in the ridge to the moored listening stations.

D. AR48

AR48 was launched 4 September 1988 in Fram Strait. This deep float (1065 m) was tracked from 5 September to 18 November 1988 passing through several eddies with a very slow general trend to the southeast as shown in Figure 23. AR48 was recontacted on 26 October 1989. This contact was very weak and only lasted for a five day period. The position record was not long enough to

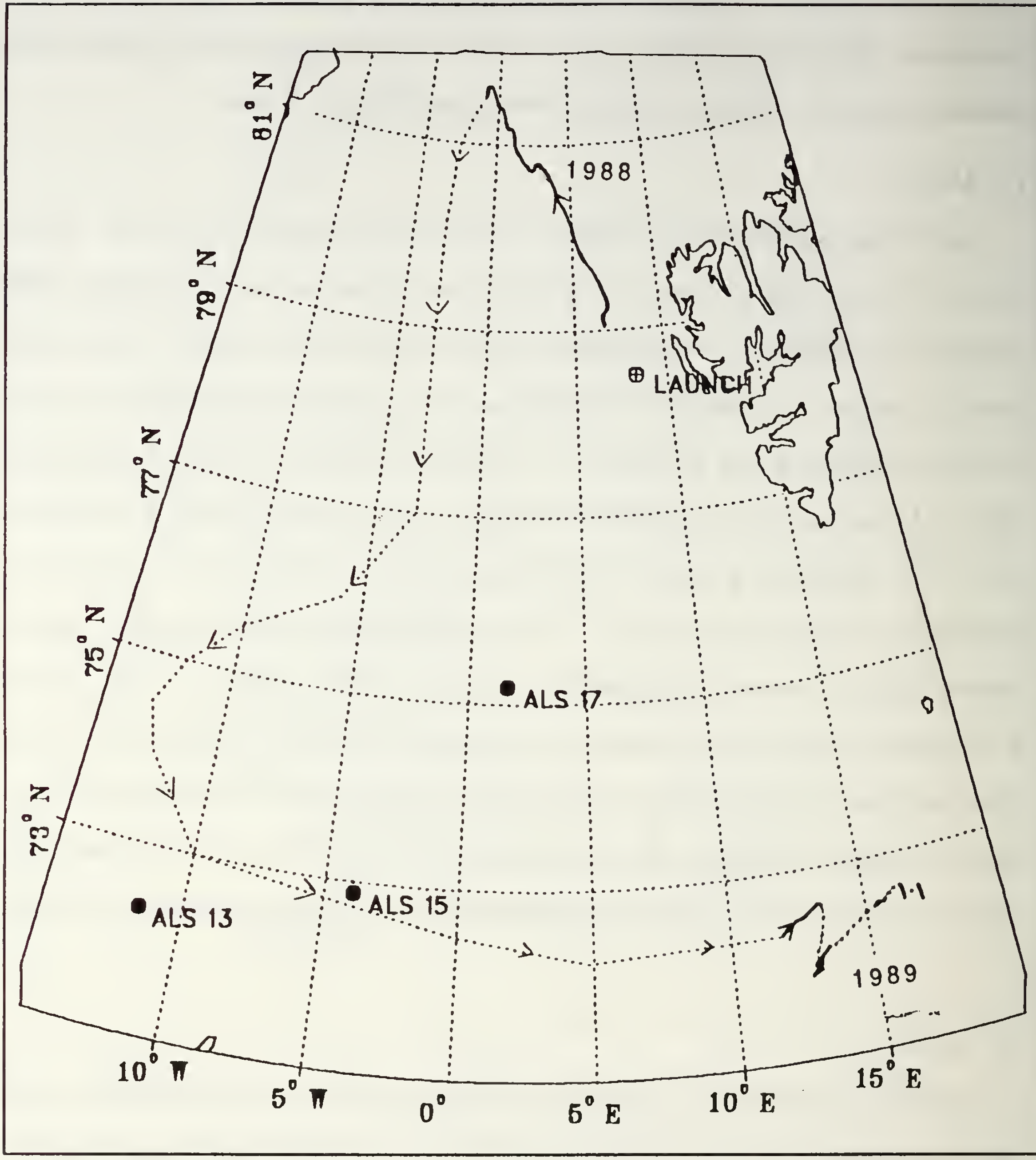

Figure 22. 1988 and 1989 trajectories of float AR57. The dotted line represents an estimated track based on the trajectory of float MZ86.

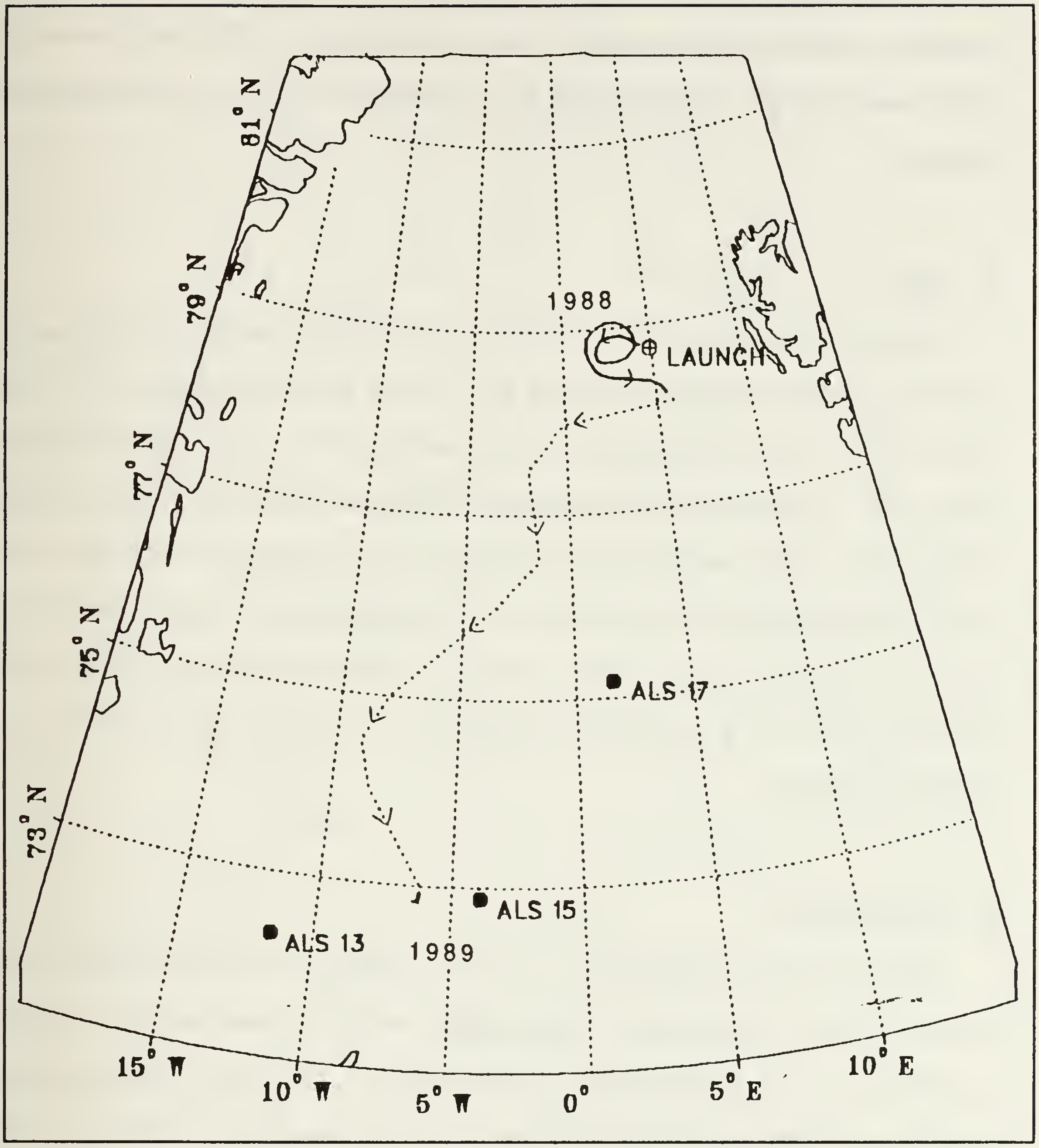

Figure 23. 1988 and 1989 trajectories of float AR48. The dotted line represents an estimated track based on the trajectory of float MZ86.

provide trajectories but was sufficient to position the float 13 months after it was launched. Again an estimated track, based on the track of MZ86 was provided to fill the tracking gap. A speed of 2.3 cm s^{-1} would be required if AR48 followed this track.

E. MZ83

MZ83 was launched on 14 April 1989 in Fram Strait and was initially tracked by the southern ALS array 13 months later. Weak contact was gained on 9 May 1990 with the float drifting to the east-northeast in the Jan Mayen Current (Figure 24). Similarly with the tracking of AR48, this short record provides little information on the motion of the float but does provide an estimate of the distance the float must have traveled in the preceding year. Based on the time between the launch and tracking period, an estimated track to achieve that position is shown as a dotted line on Figure 24. An average speed of 4.2 cm s^{-1} would be required.

F. DISCUSSION

These five float trajectories provide a glimpse of the intermediate depth currents of the Greenland Sea. Float MZ86, with its extensive drift trajectory, describes the path of intermediate depth waters as they exit Fram Strait and migrate around the Greenland Sea Gyre. Two additional floats, AR50 and AR57, show trajectories farther to the east beyond the end of the MZ86 track. AR48 provides a glimpse at the motion of the currents at 1000 m. All these floats, representing predominantly barotropic motion, indicate the flow path that the

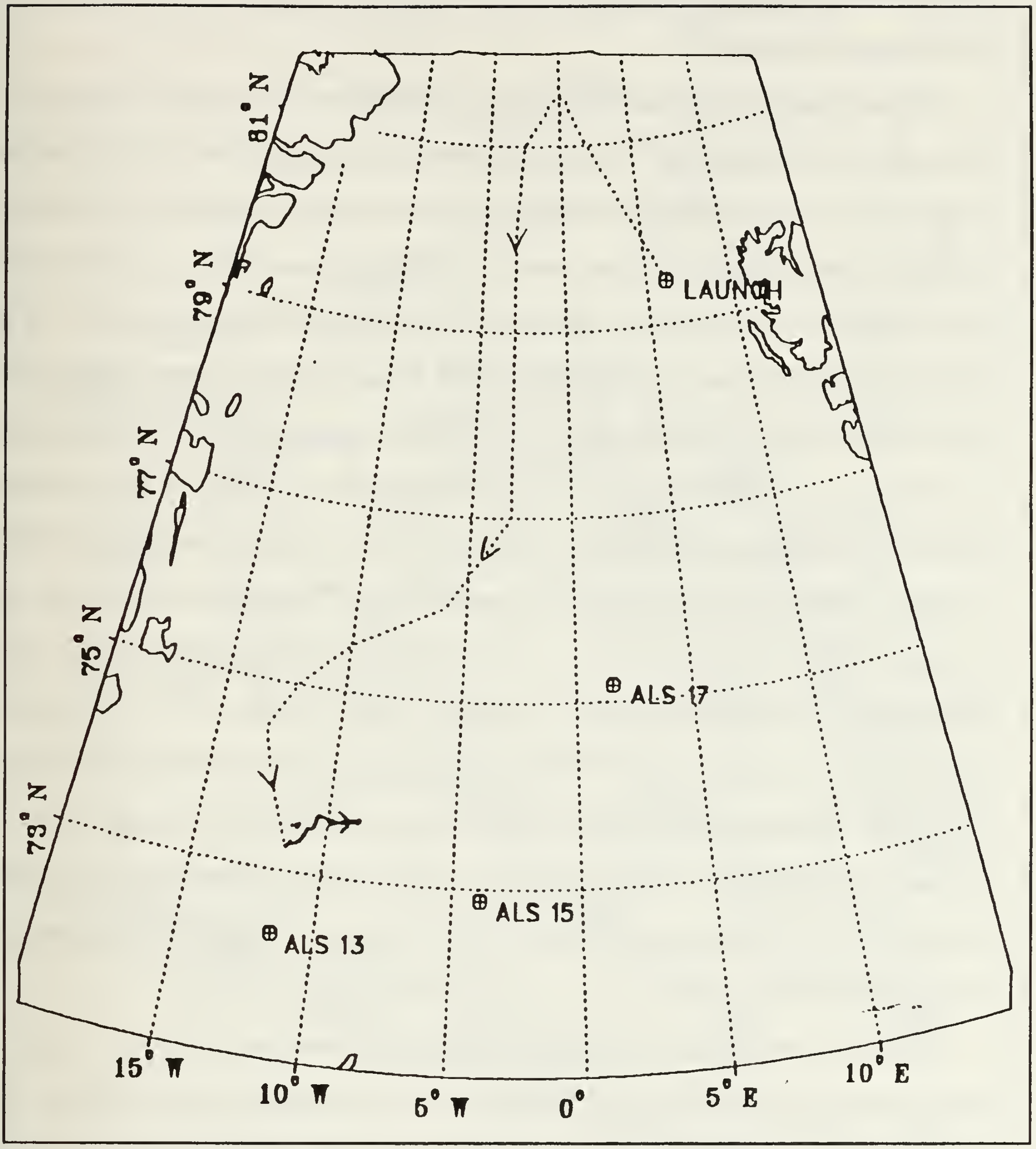

Figure 24. Launch position and tracked positions of float MZ83. The dotted line represents an estimated track based on the trajectory of float MZ86.

intermediate and deep waters most likely take as they migrate cyclonically around the Greenland Sea Gyre.

The relationship of float MZ86 to the bathymetry is provided in Figure 25. Since the variation of f, the Coriolis parameter, is very slight over the latitudinal range of this study (<2%), the bathymetry can be used to represent constant f/h contours. During leg 1 the float exited the central Boreas Basin in waters deeper than 3000 m and crossed the Greenland Fracture Zone on a trajectory to the southwest. On the southern side of the GFZ it was no longer over the deep floor of the basin but was located along the western boundary of the continental slope of Greenland. After crossing the GFZ the float, now at a depth of approximately 350 m, tracked through an area of relatively constant depth between the 2000 m and 3000 m isobaths. Its trajectory ultimately carried it partially up the slope as it proceeded to the southwest where its velocity was enhanced by this up slope effect and the resulting boundary current. As it crossed 74°N, its trajectory turned toward the east. The MZ86 signal was then interrupted by the Vesteris Seamount. As the float approached the seamount, ALS 17 lost contact when the ray path was disrupted by the seamount's shallow depth. Interestingly, the other two ALSs also lost contact on MZ86 at the same time. The loss of signal to these ALSs remains unexplained.

On this eastward leg in the JMC the velocity slowed to 3-5 cm s^{-1} while the float traversed an area of near constant depth between 2000 m and 3000 m. The float appears to exhibit some linear oscillatory motions between 10°W and 3°W (Figure 26). These features have an approximate wave length of 40 km and an amplitude of 24 km. At present, there is insufficient data to explain the cause of the meanders. A likely candidate is that they represent fingers or filaments of the

Figure 25. Plot of tracks of MZ86, AR50, and AR57 on detailed bathymetry of the Greenland Sea.

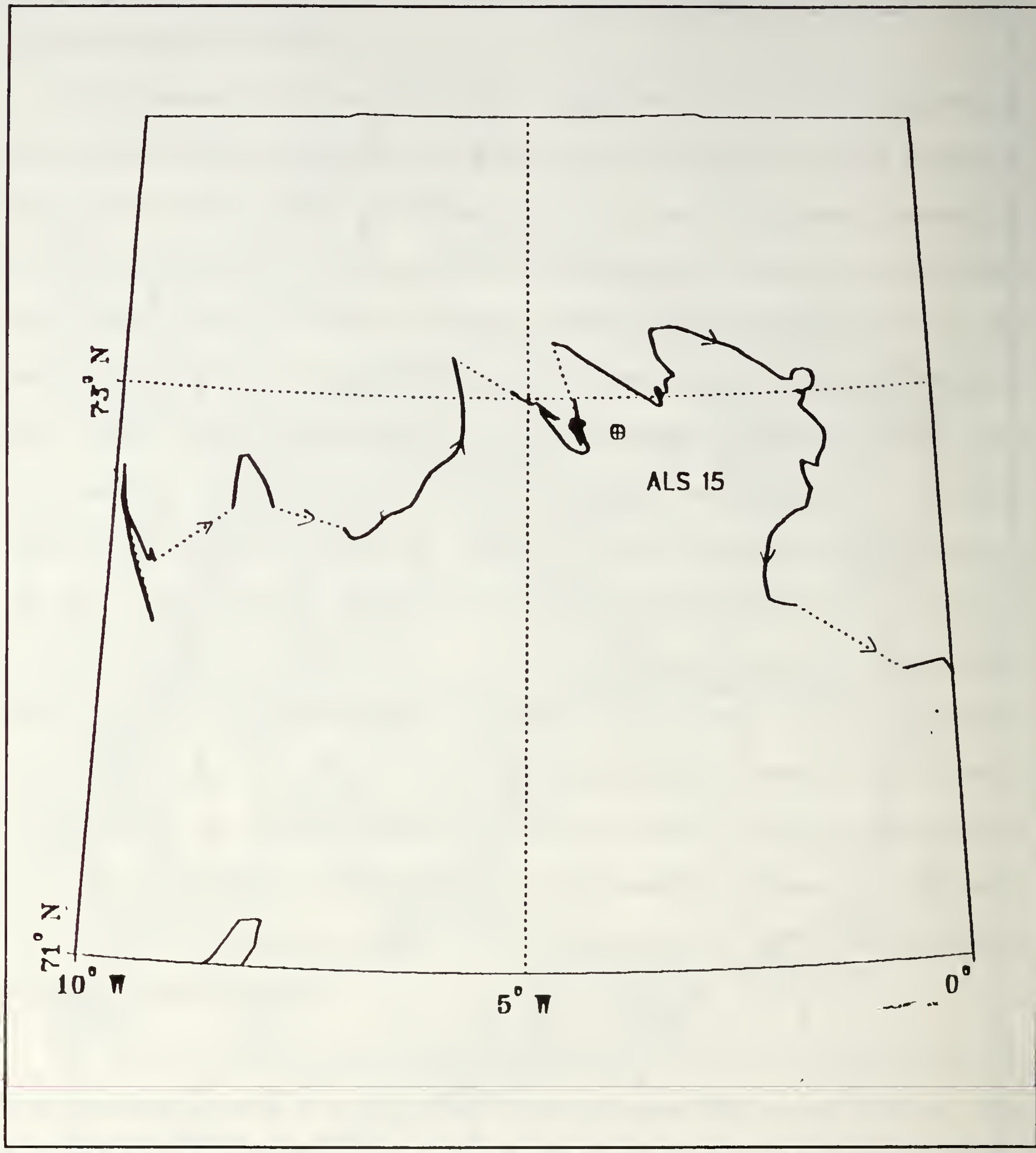

Figure 26. Detailed track of MZ86 leg 3, showing broad meanders as the float tracked to the northeast. Dotted line connects individual tracking periods.

flow that are topographically responding to the channels delineated by the breaks in the Mohns Ridge system.

At approximatly 3°W the bottom becomes more complex and the track began to cross isobaths. As the trajectory approached 2°W it took a sharp turn to the south and then the southeast. In the vicinity of 72°N, 0° the float tracked through a narrow break in Mohns Ridge and drifted along a rift valley of the ridge system. It tracked along this feature until approximately 3.5°E, whence it turned sharply to the northwest apparently caught up in a northward flowing branch of the Norwegian Atlantic Current.

During October 1989, 9 months earlier, float AR50 tracked through the same area as MZ86, crossing the Mohns Ridge slightly farther to the east. AR50 may have drifted eastward in the Jan Mayen Current, across the Greenland Sea somewhat to the south of the MZ86 track. An interannual north-south shift in the axis of the flow of the JMC has been noted by *Bourke et al.* (1991). AR50 continued tracking to the north-northwest to 74°N whereupon it turned sharply to the southeast and recrossed the ridge apparently following gaps in the ridge system near 73.5°N. The acoustic signal from AR57 was lost as the float crossed the thermohaline front marking the boundary between the Greenland and Norwegian Seas. The warmer Norwegian Sea waters direct more of the acoustic energy to deeper depths. This probably caused a reduction in the surface duct trapping associated with the Polar waters, leading to blockage of the signal by the ridge system.

Simultaneously with the tracking of float AR50, float AR57 was detected some 150 km to the east and tracked during October and November 1989 heading northeast. Because this float was well removed from the Mohns Ridge, it

was apparent that the acoustic signals must have been diffracted over the ridge as well as passing through the numerous breaks in the ridge system.

A simulation of the Greenland Sea circulation by *Legutke* (1990) showed currents very similar to these float trajectories (Figure 27). Currents at the 341 m level of this wind-forced numerical model demonstrate quite similar features as those of the trajectory of MZ86. The flow out of the Boreas Basin is similar in magnitude to that of the observed float. This feeds an intensified boundary current along the slope and leads to the easterly circulation of the Jan Mayen Current closing the Greenland Sea Gyre. This model also shows the JMC flow turning to the north-northeast between 0° and 3°E as does MZ86. The north-northwest trajectories of MZ86 and AR50 are also well depicted although Legutke shows this to occur north of 74°N. She shows velocities along the Greenland slope on the order of 20 cm s^{-1} which compares well to the 28 cm s^{-1} observed here. Also a cross section through the model showed a similar slope-trapped boundary current.

A review of the velocity series in Figure 15 showed a possible periodic signal occurring at intervals of 3-7 days. A time series analysis of this data was done on the July data at the easterly end of MZ86, leg 3. This leg was analyzed because the initial time series showed evidence that a periodic signal may be present and the tracking was for more than 31 days. Figure 28 shows a plot of the energy density spectrum and indicates a peak in the spectra at a period of just over 3 days. This float is at 500 m during this leg and the bottom is smooth leading to the conclusion that this probably relates to energy from Kelvin waves propagating along the flow.

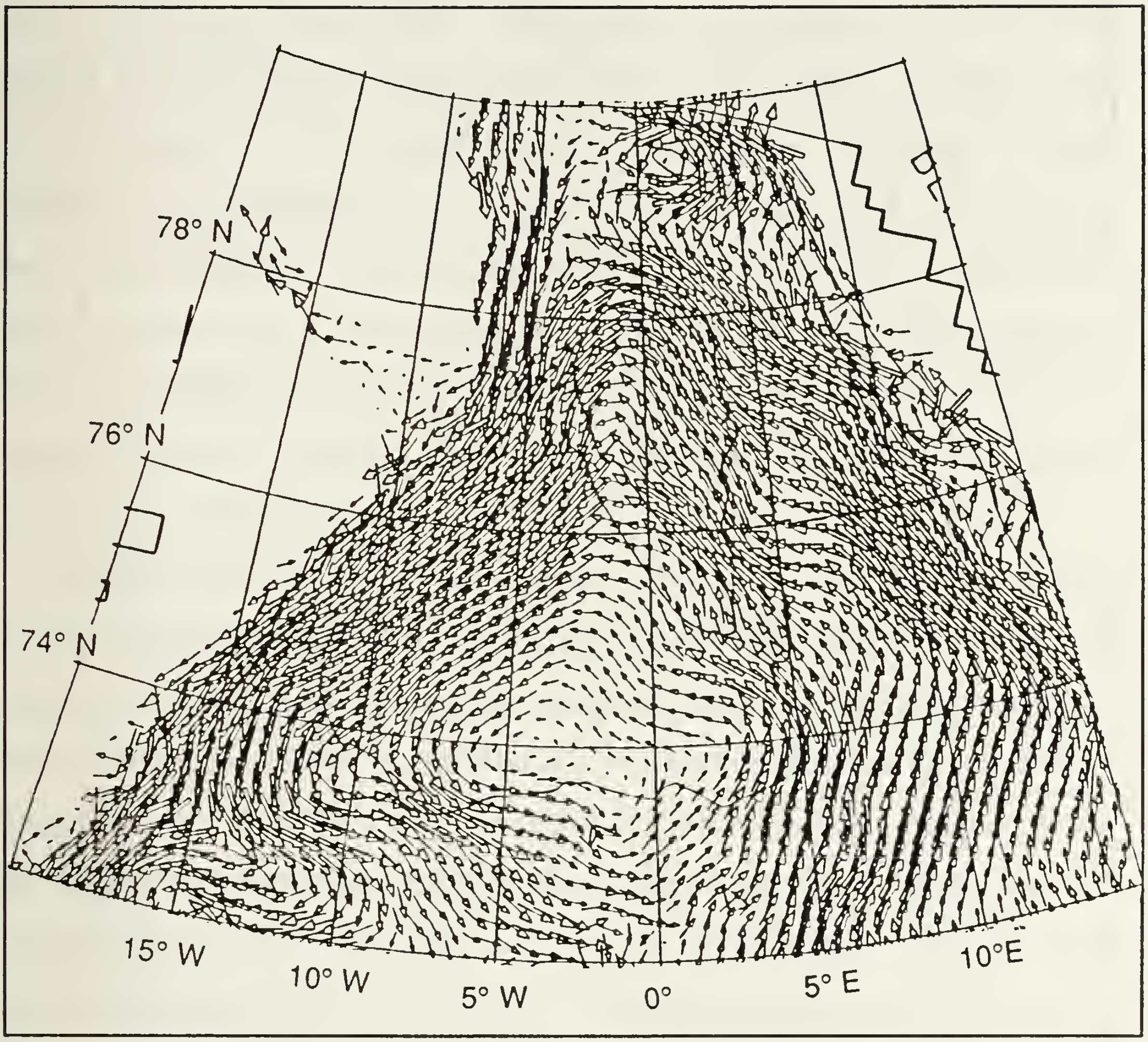

Figure 27. Current velocity at the 341 m level of the essentially barotropic and wind-forced model of *Legutke* (1990). Single line arrows represent speed <3cm s^{-1} and hollow arrows represent speed > 3cm s^{-1}.

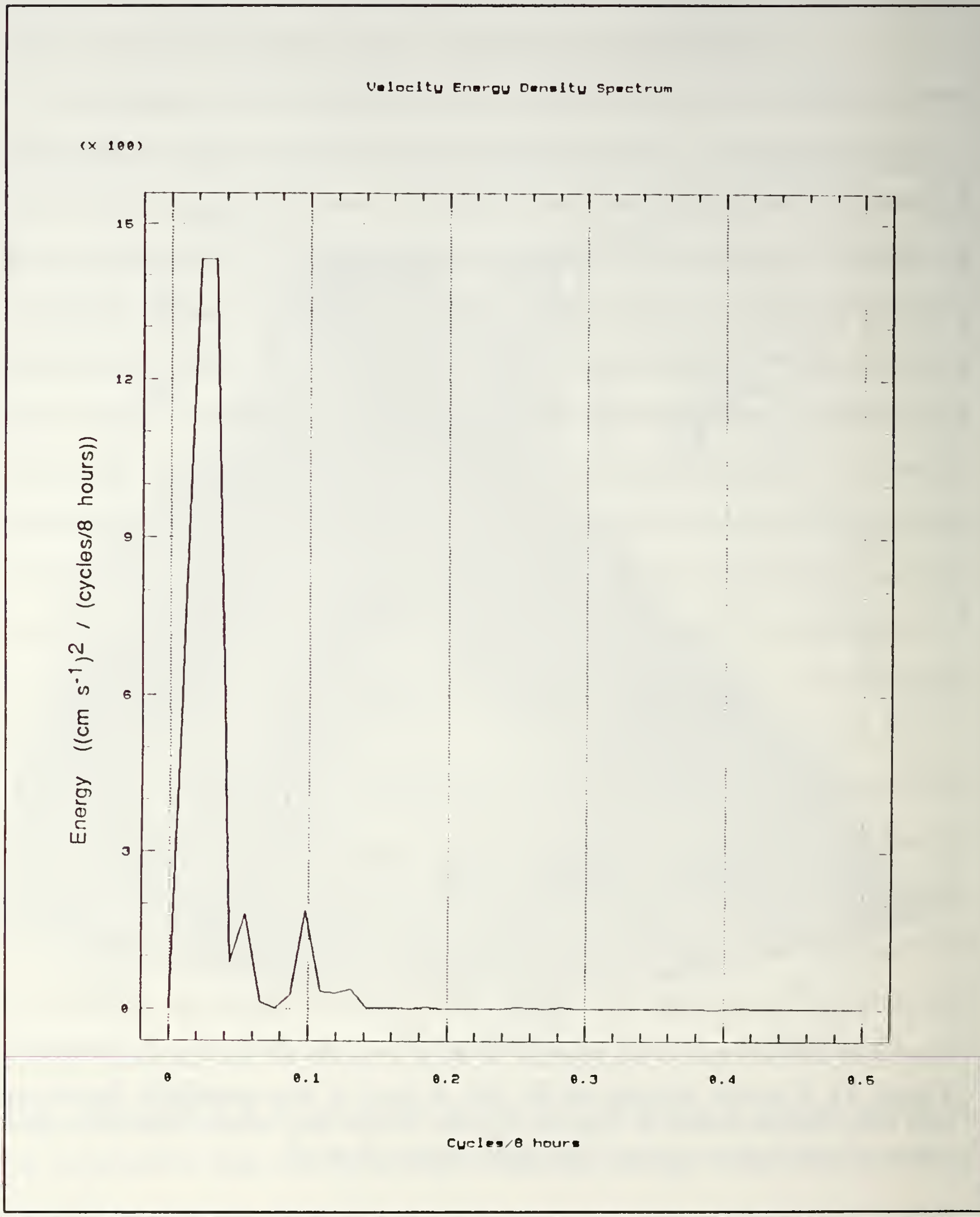

Figure 28 Energy density spectrum of the MZ86 velocity series from 3 July 1990 to 4 August 1990.

IV. CONCLUSIONS

A better understanding of the intermediate depth circulation in the Greenland Sea was the goal of this study. Trajectories of acoustically-tracked drifting SOFAR floats ballasted for depths ranging from 200 to 500 m were determined by processing the time of arrival data from a deployment of moored acoustic receivers in the Greenland Sea from September 1989 to August 1990. Sixteen floats were launched in Fram Strait during 1988 and 1989. Five of the sixteen floats launched were tracked during the 1989/90 deployment of the receivers. One float (MZ86) provided tracking information for ten months of the deployment period. The other floats provided tracking information ranging from several days to two months.

A strong flow (17 cm s^{-1}) was observed as MZ86 exited Fram Strait through the Boreas Basin and crossed the Greenland Fracture Zone (GFZ). The trajectory then moved parallel to the Greenland continental slope where the flow velocity at 350 m increased to 28 cms^{-1}, characteristic of a bottom boundary current trapped along the slope. Near 74°N the float turned to the southeast as it approached the Jan Mayen Fracture Zone (JMFZ) and continued to the east to close the Greenland Sea Gyre. This portion of the flow is strongly barotropic with observed velocities at 500 m of 3-5 cm s^{-1}, similar to that recorded previously by a year-long current meter mooring intersected by the float. In the vicinity of 3°E, filaments of the Norwegian Atlantic Current (NAC) crossed through breaks in the Mohns Ridge and pushed the trajectory to the northwest, illustrating how the Jan Mayen Current merges with the NAC at intermediate depths .

Other features observed include bathymetric blocking of the signal especially as the float passed close to the Vesteris Seamount and also across Mohns Ridge. Because of the complexity of the Mohns Ridge topography, the signal was intermittently received at the listening arrays during its easterly drift. Meanders were observed as MZ86 drifted eastward in the Jan Mayen Current with a period of approximately three days, a wavelength of 40 km and an amplitude of 24 km. No indication of eddy energy was apparent during the transit along the Greenland slope nor when exiting the Boreas Basin.

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APPENDIX A

MZ86 POSITIONS

Positions of MZ86 from 27 September 1989 to 4 August 1990. Rows of zeros are used to delineate breaks in the tracking record. The format of the data is month day hour minute, latitude, longitude as shown below. Negative longitudes represent westerly longitudes.

MMDDHHMM	LAT	LON
10301802	78.235	-8.225

MMDDHHMM	LAT	LON
927 302	77.573	-0.517
9271102	77.515	-0.459
9271902	77.464	-0.512
928 302	77.417	-0.400
9281102	77.372	-0.290
9281902	77.329	-0.190
929 302	77.286	-0.109
9291102	77.247	-0.059
9291902	77.216	-0.050
930 302	77.190	-0.081
9301102	77.164	-0.133
9301902	77.138	-0.197
10 1 302	77.111	-0.265
10 11102	77.084	-0.338
10 11902	77.058	-0.426
10 2 302	77.032	-0.562
10 21102	77.006	-0.749
10 21902	76.978	-0.948
10 3 302	76.951	-1.152
10 31102	76.926	-1.350
10 31902	76.911	-1.519
10 4 302	76.906	-1.651
10 41102	76.902	-1.774
10 41902	76.898	-1.894
10 5 302	76.890	-2.033
10 51102	76.875	-2.188
10 51902	76.858	-2.342
10 6 302	76.840	-2.491
10 61102	76.822	-2.619
10 61902	76.799	-2.740
10 7 302	76.770	-2.861
10 71102	76.738	-2.986
10 71902	76.704	-3.124
10 8 302	76.669	-3.263
10 81102	76.633	-3.400
10 81902	76.597	-3.529
10 9 302	76.560	-3.659
10 91102	76.523	-3.790
10 91902	76.490	-3.927
1010 302	76.461	-4.083
10101102	76.430	-4.274
10101902	76.397	-4.521
1011 302	76.357	-4.809
10111102	76.307	-5.115
10111902	76.248	-5.427
1012 302	76.187	-5.738
10121102	76.124	-6.041
10121902	76.062	-6.302
1013 302	76.004	-6.536
10131102	75.954	-6.765
10131902	75.909	-6.998
1014 302	75.865	-7.231
10141102	75.825	-7.464
10141902	75.787	-7.697
1015 302	75.751	-7.932
10151102	75.716	-8.161
10151902	75.682	-8.380
1016 302	75.653	-8.593
10161102	75.631	-8.808
10161902	75.612	-9.047

MMDDHHMM	LAT	LON
1017 302	75.594	-9.309
10171102	75.576	-9.576
10171902	75.557	-9.842
1018 302	75.534	-10.104
10181102	75.504	-10.366
10181902	75.461	-10.621
1019 302	75.407	-10.859
10191102	75.342	-11.054
10191902	75.271	-11.211
1020 302	75.195	-11.349
10201102	75.117	-11.480
10201902	75.037	-11.611
1021 302	74.957	-11.747
10211102	74.876	-11.905
10211902	74.800	-12.067
1022 302	74.729	-12.225
10221102	74.660	-12.379
10221902	74.590	-12.527
1023 302	74.516	-12.670
10231102	74.442	-12.807
10231902	74.366	-12.926
1024 302	74.293	-13.004
10241102	74.225	-13.032
10241902	74.164	-13.027
1025 302	74.116	-13.010
10251102	74.080	-12.986
10251902	74.055	-12.958
1026 302	74.038	-12.936
10261102	74.025	-12.916
10261902	74.015	-12.897
1027 302	74.004	-12.883
10271102	73.992	-12.879
10271902	73.980	-12.874
1028 302	73.967	-12.861
10281102	73.948	-12.844
10281902	73.923	-12.822
1029 302	73.898	-12.797
10291102	73.874	-12.772
10291902	73.850	-12.744
1030 302	73.829	-12.711
10301102	73.812	-12.682
10301902	73.794	-12.660
1031 302	73.772	-12.644
10311102	73.748	-12.621
10311902	73.725	-12.593
11 1 302	73.702	-12.566
11 11102	73.680	-12.542
11 11902	73.659	-12.533
11 2 302	73.640	-12.536
11 21102	73.626	-12.539
11 21902	73.614	-12.538
11 3 302	73.604	-12.539
11 31102	73.594	-12.541
11 31902	73.586	-12.537
11 4 302	73.584	-12.527
11 41102	73.585	-12.516
11 41902	73.587	-12.505
11 5 302	73.587	-12.522
11 51102	73.579	-12.571
11 51902	73.563	-12.618

MMDDHHMM	LAT	LON
11 6 302	73.545	-12.653
11 61102	73.527	-12.675
11 61902	73.510	-12.692
11 7 302	73.497	-12.711
11 71102	73.482	-12.732
11 71902	73.464	-12.750
11 8 302	73.440	-12.741
11 81102	73.413	-12.711
11 81902	73.394	-12.684
11 9 302	73.396	-12.676
11 91102	73.397	-12.679
0 0 0	0.000	0.000
0 0 0	0.000	0.000
11131102	73.760	-12.694
11131902	73.648	-12.431
1114 302	73.692	-12.443
11141102	73.691	-12.455
11141902	73.690	-12.467
1115 302	73.687	-12.455
11151102	73.683	-12.415
11151902	73.673	-12.376
1116 302	73.661	-12.336
11161102	73.647	-12.300
11161902	73.633	-12.264
1117 302	73.619	-12.228
11171102	73.606	-12.194
11171902	73.595	-12.160
1118 302	73.584	-12.124
11181102	73.574	-12.080
11181902	73.561	-12.029
1119 302	73.547	-11.979
11191102	73.529	-11.931
11191902	73.506	-11.901
1120 302	73.479	-11.886
11201102	73.450	-11.871
11201902	73.420	-11.852
1121 302	73.389	-11.813
11211102	73.359	-11.755
11211902	73.330	-11.690
1122 302	73.304	-11.624
11221102	73.280	-11.559
11221902	73.262	-11.506
1123 302	73.250	-11.473
11231102	73.241	-11.451
11231902	73.235	-11.432
1124 302	73.229	-11.410
11241102	73.224	-11.381
11241902	73.219	-11.335
1125 302	73.211	-11.259
11251102	73.203	-11.161
11251902	73.195	-11.051
1126 302	73.187	-10.925
11261102	73.172	-10.747
11261902	73.167	-10.629
0 0 0	0.000	0.000
0 0 0	0.000	0.000
1261902	72.177	-9.434
127 302	72.390	-9.717
1271102	72.591	-9.906
1271902	72.658	-9.903

MMDDHHMM	LAT	LON
128 302	72.629	-9.893
1281102	72.601	-9.880
1281902	72.573	-9.866
129 302	72.551	-9.848
1291102	72.534	-9.822
1291902	72.518	-9.790
130 302	72.502	-9.755
1301102	72.484	-9.719
1301902	72.465	-9.683
131 302	72.445	-9.647
1311102	72.426	-9.613
1311902	72.409	-9.583
2 1 302	72.395	-9.558
2 11102	72.389	-9.543
2 11902	72.389	-9.531
2 2 302	72.394	-9.524
2 21102	72.400	-9.518
2 21902	72.407	-9.513
2 3 302	72.417	-9.513
2 31102	72.388	-9.461
0 0 0	0.000	0.000
0 0 0	0.000	0.000
213 302	72.594	-8.563
2131102	72.683	-8.547
2131902	72.763	-8.512
214 302	72.772	-8.421
2141102	72.736	-8.330
2141902	72.701	-8.239
215 302	72.667	-8.170
2151102	72.636	-8.132
2151902	72.604	-8.091
0 0 0	0.000	0.000
0 0 0	0.000	0.000
2171102	72.537	-7.224
2171902	72.512	-7.151
218 302	72.505	-7.084
2181102	72.509	-7.021
2181902	72.517	-6.958
219 302	72.528	-6.900
2191102	72.542	-6.851
2191902	72.558	-6.802
220 302	72.573	-6.754
2201102	72.586	-6.697
2201902	72.595	-6.628
221 302	72.603	-6.557
2211102	72.611	-6.487
2211902	72.622	-6.426
222 302	72.641	-6.375
2221102	72.664	-6.330
2221902	72.689	-6.287
223 302	72.714	-6.242
2231102	72.737	-6.186
2231902	72.754	-6.119
224 302	72.768	-6.051
2241102	72.782	-5.985
2241902	72.797	-5.924
225 302	72.814	-5.872
2251102	72.837	-5.833
2251902	72.869	-5.810
226 302	72.906	-5.804

MMDDHHMM	LAT	LON
2261102	72.947	-5.809
2261902	72.990	-5.823
227 302	73.035	-5.849
2271102	73.084	-5.887
2271902	73.136	-5.935
0 0 0	0.000	0.000
0 0 0	0.000	0.000
328 302	73.023	-5.222
3281102	72.979	-4.946
3281902	72.983	-4.898
329 302	72.975	-4.867
3291102	72.968	-4.836
3291902	72.961	-4.807
330 302	72.955	-4.780
3301102	72.949	-4.753
3301902	72.942	-4.723
331 302	72.935	-4.691
3311102	72.929	-4.660
3311902	72.927	-4.632
4 1 302	72.926	-4.614
4 11102	72.927	-4.616
4 11902	72.931	-4.644
4 2 302	72.937	-4.687
4 21102	72.943	-4.735
4 21902	72.949	-4.780
4 3 302	72.953	-4.819
4 31102	72.954	-4.847
4 31902	72.948	-4.845
4 4 302	72.936	-4.813
4 41102	72.922	-4.771
4 41902	72.906	-4.725
4 5 302	72.890	-4.681
4 51102	72.876	-4.641
4 51902	72.862	-4.605
4 6 302	72.850	-4.570
4 61102	72.838	-4.535
4 61902	72.826	-4.485
4 7 302	72.817	-4.423
4 71102	72.811	-4.363
4 71902	72.809	-4.309
4 8 302	72.814	-4.269
4 81102	72.824	-4.257
4 81902	72.838	-4.279
4 9 302	72.854	-4.316
4 91102	72.871	-4.358
4 91902	72.888	-4.401
410 302	72.903	-4.441
4101102	72.916	-4.463
4101902	72.924	-4.457
411 302	72.926	-4.427
4111102	72.925	-4.391
4111902	72.921	-4.353
412 302	72.915	-4.319
4121102	72.908	-4.301
4121902	72.902	-4.308
413 302	72.901	-4.331
4131102	72.903	-4.359
4131902	72.905	-4.388
414 302	72.908	-4.416
4141102	72.909	-4.437

MMDDHHMM	LAT	LON
4141902	72.910	-4.456
415 302	72.909	-4.472
4151102	72.907	-4.483
4151902	72.903	-4.488
416 302	72.900	-4.490
4161102	72.898	-4.491
4161902	72.896	-4.491
417 302	72.893	-4.484
4171102	72.887	-4.465
4171902	72.875	-4.436
418 302	72.863	-4.402
4181102	72.849	-4.367
4181902	72.956	-4.409
419 302	72.852	-4.311
0 0 0	0.000	0.000
0 0 0	0.000	0.000
4281902	73.195	-4.698
429 302	73.182	-4.522
4291102	73.140	-4.316
4291902	73.104	-4.122
430 302	73.070	-3.938
4301102	73.039	-3.769
4301902	73.013	-3.620
5 1 302	72.991	-3.501
5 11102	72.974	-3.418
5 11902	72.968	-3.371
5 2 302	72.970	-3.351
5 21102	72.975	-3.347
5 21902	72.981	-3.352
5 3 302	72.988	-3.362
5 31102	72.995	-3.373
5 31902	73.002	-3.385
5 4 302	73.011	-3.399
5 41102	73.020	-3.412
5 41902	73.029	-3.415
5 5 302	73.032	-3.400
5 51102	73.028	-3.382
5 51902	73.020	-3.369
5 6 302	73.011	-3.361
5 61102	73.003	-3.357
5 61902	73.000	-3.348
5 7 302	73.003	-3.336
5 71102	73.007	-3.323
5 71902	73.010	-3.314
5 8 302	73.011	-3.306
5 81102	73.012	-3.297
5 81902	73.013	-3.290
5 9 302	73.014	-3.285
5 91102	73.016	-3.280
5 91902	73.021	-3.279
510 302	73.031	-3.284
5101102	73.041	-3.293
5101902	73.050	-3.297
511 302	73.056	-3.286
5111102	73.061	-3.257
5111902	73.066	-3.225
512 302	73.071	-3.193
5121102	73.081	-3.204
5121902	73.097	-3.263
513 302	73.115	-3.323

MMDDHHMM	LAT	LON
5131102	73.134	-3.380
5131902	73.154	-3.414
514 302	73.175	-3.431
5141102	73.196	-3.447
5141902	73.216	-3.463
515 302	73.229	-3.473
5151102	73.235	-3.457
5151902	73.239	-3.410
516 302	73.242	-3.348
5161102	73.245	-3.283
5161902	73.247	-3.211
517 302	73.244	-3.124
5171102	73.233	-3.012
5171902	73.218	-2.885
518 302	73.202	-2.750
5181102	73.187	-2.615
5181902	73.173	-2.482
519 302	73.158	-2.379
5191102	73.141	-2.298
5191902	73.125	-2.217
520 302	73.110	-2.137
5201102	73.100	-2.075
5201902	73.090	-2.032
521 302	73.080	-1.992
5211102	73.070	-1.947
5211902	73.060	-1.894
522 302	73.050	-1.841
5221102	73.045	-1.788
5221902	73.044	-1.755
523 302	73.044	-1.742
5231102	73.044	-1.731
5231902	73.048	-1.725
524 302	73.056	-1.720
5241102	73.065	-1.708
5241902	73.073	-1.679
525 302	73.077	-1.644
5251102	73.078	-1.607
5251902	73.078	-1.566
526 302	73.076	-1.525
5261102	73.070	-1.495
5261902	73.063	-1.482
527 302	73.056	-1.472
5271102	73.051	-1.461
5271902	73.047	-1.453
528 302	73.041	-1.454
5281102	73.032	-1.456
5281902	73.023	-1.461
529 302	73.015	-1.473
5291102	73.009	-1.495
5291902	73.005	-1.525
530 302	73.001	-1.557
5301102	72.997	-1.587
5301902	72.995	-1.616
531 302	72.998	-1.645
5311102	73.000	-1.666
5311902	73.002	-1.674
6 1 302	73.003	-1.669
6 11102	73.003	-1.652
6 11902	73.002	-1.632
6 2 302	72.998	-1.609

MMDDHHMM	LAT	LON
6 21102	72.993	-1.590
6 21902	72.987	-1.580
6 3 302	72.980	-1.584
6 31102	72.973	-1.599
6 31902	72.967	-1.616
6 4 302	72.961	-1.633
6 41102	72.955	-1.648
6 41902	72.945	-1.621
6 5 302	72.928	-1.556
6 51102	72.907	-1.490
6 51902	72.885	-1.428
6 6 302	72.865	-1.378
6 61102	72.847	-1.353
6 61902	72.830	-1.353
6 7 302	72.813	-1.362
6 71102	72.800	-1.375
6 71902	72.790	-1.392
6 8 302	72.781	-1.410
6 81102	72.771	-1.429
6 81902	72.762	-1.444
6 9 302	72.754	-1.454
6 91102	72.749	-1.459
6 91902	72.745	-1.460
610 302	72.741	-1.461
6101102	72.737	-1.461
6101902	72.735	-1.459
611 302	72.735	-1.457
6111102	72.737	-1.457
6111902	72.739	-1.457
612 302	72.740	-1.460
6121102	72.741	-1.470
6121902	72.742	-1.487
613 302	72.743	-1.508
6131102	72.745	-1.529
6131902	72.748	-1.552
614 302	72.751	-1.578
6141102	72.753	-1.604
6141902	72.755	-1.630
615 302	72.756	-1.643
6151102	72.757	-1.643
6151902	72.758	-1.643
616 302	72.758	-1.644
6161102	72.756	-1.647
6161902	72.751	-1.650
617 302	72.744	-1.651
6171102	72.732	-1.646
6171902	72.717	-1.636
618 302	72.701	-1.619
6181102	72.685	-1.597
6181902	72.672	-1.572
619 302	72.665	-1.546
6191102	72.662	-1.538
6191902	72.658	-1.548
620 302	72.651	-1.559
6201102	72.639	-1.570
6201902	72.626	-1.581
621 302	72.614	-1.593
6211102	72.606	-1.603
6211902	72.601	-1.612
622 302	72.597	-1.628

MMDDHHMM	LAT	LON	MMDDHHMM	LAT	LON
6221102	72.593	-1.667	7151102	72.349	3.022
6221902	72.588	-1.733	7151902	72.355	3.031
623 302	72.574	-1.812	716 302	72.361	3.043
6231102	72.555	-1.893	7161102	72.367	3.061
6231902	72.536	-1.971	7161902	72.371	3.081
624 302	72.518	-2.034	717 302	72.375	3.098
6241102	72.502	-2.071	7171102	72.382	3.114
6241902	72.487	-2.087	7171902	72.395	3.150
625 302	72.471	-2.098	718 302	72.408	3.212
6251102	72.455	-2.108	7181102	72.419	3.278
6251902	72.440	-2.119	7181902	72.428	3.348
626 302	72.425	-2.129	719 302	72.436	3.413
6261102	72.410	-2.140	7191102	72.446	3.473
6261902	72.394	-2.150	7191902	72.467	3.520
627 302	72.374	-2.161	720 302	72.498	3.543
6271102	72.352	-2.162	7201102	72.528	3.527
6271902	72.329	-2.150	7201902	72.558	3.487
628 302	72.306	-2.137	721 302	72.585	3.436
6281102	72.289	-2.125	7211102	72.602	3.381
6281902	72.278	-2.067	7211902	72.607	3.329
629 302	72.267	-1.941	722 302	72.607	3.293
6291102	72.259	-1.809	7221102	72.604	3.285
0 0 0	0.000	0.000	7221902	72.602	3.294
0 0 0	0.000	0.000	723 302	72.602	3.306
7 31102	72.013	-0.542	7231102	72.606	3.314
7 31902	72.022	-0.372	7231902	72.615	3.317
7 4 302	72.032	-0.163	724 302	72.626	3.296
7 41102	72.034	-0.092	7241102	72.638	3.249
7 41902	72.026	-0.071	7241902	72.650	3.193
7 5 302	72.015	-0.051	725 302	72.662	3.135
7 51102	72.002	-0.026	7251102	72.677	3.095
7 51902	71.991	0.009	7251902	72.691	3.072
7 6 302	71.983	0.066	726 302	72.705	3.049
7 61102	71.983	0.159	7261102	72.719	3.024
7 61902	71.997	0.298	7261902	72.733	2.967
7 7 302	72.022	0.461	727 302	72.745	2.878
7 71102	72.051	0.636	7271102	72.753	2.788
7 71902	72.084	0.815	7271902	72.762	2.697
7 8 302	72.117	0.993	728 302	72.771	2.604
7 81102	72.148	1.168	7281102	72.780	2.516
7 81902	72.173	1.344	7281902	72.785	2.467
7 9 302	72.189	1.530	729 302	72.788	2.455
7 91102	72.204	1.727	7291102	72.791	2.443
7 91902	72.218	1.926	7291902	72.794	2.431
710 302	72.233	2.120	730 302	72.802	2.417
7101102	72.248	2.306	7301102	72.816	2.382
7101902	72.264	2.469	7301902	72.831	2.333
711 302	72.279	2.590	731 302	72.846	2.284
7111102	72.292	2.676	7311102	72.861	2.248
7111902	72.301	2.745	7311902	72.875	2.233
712 302	72.306	2.806	8 1 302	72.885	2.220
7121102	72.309	2.864	8 11102	72.891	2.205
7121902	72.313	2.920	8 11902	72.894	2.191
713 302	72.317	2.963	8 2 302	72.894	2.180
7131102	72.323	2.991	8 21102	72.893	2.168
7131902	72.329	3.009	8 21902	72.892	2.151
714 302	72.335	3.016	8 3 302	72.891	2.132
7141102	72.338	3.017	8 31102	72.889	2.113
7141902	72.340	3.015	8 31902	72.890	2.092
715 302	72.344	3.017	8 4 302	72.883	2.087

APPENDIX B

AR50 POSITIONS

Positions of AR50 from 24 September 1989 to 25 November 1989. Rows of zeros are used to delineate breaks in the tracking record. The format of the data is month day hour minute, latitude, longitude as shown below. Negative longitudes represent westerly longitudes.

MMDDHHMM	LAT	LON
10301802	78.235	-8.225

MMDDHHMM	LAT	LON
924 901	72.244	4.819
9241701	72.268	4.703
925 101	72.292	4.614
925 901	72.318	4.565
9251701	72.345	4.518
926 101	72.373	4.462
926 901	72.400	4.396
9261701	72.424	4.330
927 101	72.449	4.263
927 901	72.472	4.206
9271701	72.497	4.169
928 101	72.521	4.138
928 901	72.546	4.107
9281701	72.568	4.074
929 101	72.587	4.033
929 901	72.607	3.991
9291701	72.626	3.949
930 101	72.647	3.905
930 901	72.668	3.847
9301701	72.690	3.775
10 1 101	72.710	3.703
10 1 901	72.730	3.637
10 11701	72.749	3.578
10 2 101	72.769	3.520
10 2 901	72.791	3.462
10 21701	72.813	3.405
10 3 101	72.834	3.350
10 3 901	72.855	3.295
10 31701	72.876	3.239
10 4 101	72.897	3.185
10 4 901	72.918	3.131
10 41701	72.939	3.082
10 5 101	72.960	3.039
10 5 901	72.980	2.995
10 51701	73.001	2.953
10 6 101	73.021	2.912
10 6 901	73.041	2.874
10 61701	73.061	2.840
10 7 101	73.079	2.807
10 7 901	73.097	2.776
10 71701	73.114	2.746
10 8 101	73.132	2.719
10 8 901	73.152	2.697
10 81701	73.174	2.679
10 9 101	73.196	2.660
10 9 901	73.218	2.643
10 91701	73.240	2.637
1010 101	73.261	2.650
1010 901	73.281	2.675
10101701	73.302	2.703
1011 101	73.321	2.730
1011 901	73.340	2.754
10111701	73.358	2.769
1012 101	73.376	2.766
1012 901	73.396	2.753
10121701	73.418	2.734
1013 101	73.440	2.705
1013 901	73.462	2.668
10131701	73.483	2.629
1014 101	73.504	2.592

MMDDHHMM	LAT	LON
1014 901	73.524	2.557
10141701	73.546	2.543
1015 101	73.568	2.551
1015 901	73.591	2.569
10151701	73.613	2.590
1016 101	73.635	2.610
1016 901	73.655	2.627
10161701	73.673	2.644
1017 101	73.688	2.665
1017 901	73.702	2.694
10171701	73.714	2.725
1018 101	73.727	2.756
1018 901	73.740	2.787
10181701	73.753	2.820
1019 101	73.768	2.863
1019 901	73.784	2.909
10191701	73.799	2.954
1020 101	73.815	2.992
1020 901	73.828	3.009
10201701	73.840	3.009
1021 101	73.850	3.004
1021 901	73.860	2.997
10211701	73.870	2.998
1022 101	73.878	3.005
1022 901	73.885	3.012
10221701	73.892	3.021
1023 101	73.899	3.030
1023 901	73.906	3.039
10231701	73.911	3.036
1024 101	73.916	3.020
1024 901	73.920	3.005
10241701	73.925	2.994
1025 101	73.930	2.985
1025 901	73.935	2.977
10251701	73.941	2.962
1026 101	73.944	2.936
1026 901	73.945	2.911
10261701	73.946	2.886
1027 101	73.946	2.866
1027 901	73.948	2.862
10271701	73.951	2.879
1028 101	73.955	2.912
1028 901	73.959	2.951
10281701	73.963	2.991
1029 101	73.966	3.028
1029 901	73.969	3.064
10291701	73.977	3.061
1030 101	74.031	2.576
0 0 0	0.000	0.000
0 0 0	0.000	0.000
11 2 901	74.009	3.256
11 21701	74.019	3.269
11 3 101	74.021	3.282
11 3 901	74.015	3.284
11 31701	74.010	3.279
11 4 101	74.004	3.276
11 4 901	74.000	3.275
11 41701	73.996	3.282
11 5 101	73.992	3.299
11 5 901	73.988	3.320

MMDDHHMM	LAT	LON
11 51701	73.984	3.342
11 6 101	73.979	3.364
11 6 901	73.973	3.387
11 61701	73.967	3.414
11 7 101	73.960	3.452
11 7 901	73.953	3.499
11 71701	73.946	3.549
11 8 101	73.939	3.601
11 8 901	73.932	3.652
11 81701	73.924	3.703
11 9 101	73.916	3.753
11 9 901	73.907	3.804
11 91701	73.897	3.859
1110 101	73.887	3.916
1110 901	73.875	3.973
11101701	73.863	4.028
1111 101	73.850	4.082
1111 901	73.838	4.136
11111701	73.826	4.190
1112 101	73.813	4.249
1112 901	73.801	4.316
11121701	73.789	4.383
1113 101	73.777	4.450
1113 901	73.766	4.513
11131701	73.755	4.539
1114 101	73.743	4.582
0 0 0	0.000	0.000
0 0 0	0.000	0.000
1118 101	73.635	5.569
1118 901	73.627	5.685
11181701	73.625	5.802
1119 101	73.627	5.931
1119 901	73.629	6.061
11191701	73.631	6.190
1120 101	73.632	6.312
1120 901	73.630	6.425
11201701	73.625	6.522
1121 101	73.617	6.599
1121 901	73.605	6.665
11211701	73.591	6.724
1122 101	73.576	6.779
1122 901	73.561	6.832
11221701	73.545	6.885
1123 101	73.530	6.943
1123 901	73.518	7.013
11231701	73.510	7.096
1124 101	73.502	7.185
1124 901	73.494	7.275
11241701	73.483	7.369
1125 101	73.473	7.463

APPENDIX C

AR57 POSITIONS

Positions of AR57 from 22 September 1989 to 19 November 1989 . Rows of zeros are used to delineate breaks in the tracking record. The format of the data is month day hour minute, latitude, longitude as shown below. Negative longitudes represent westerly longitudes.

MMDDHHMM	LAT	LON
10301802	78.235	-8.225

MMDDHHMM	LAT	LON
9221011	72.341	11.858
923 211	72.393	12.045
9231811	72.410	12.128
924 211	72.421	12.175
9241011	72.433	12.224
9241811	72.444	12.273
925 211	72.456	12.322
9251011	72.464	12.371
9251811	72.469	12.418
926 211	72.474	12.463
9261011	72.479	12.505
9261811	72.484	12.545
927 211	72.488	12.585
9271011	72.492	12.625
9271811	72.497	12.667
928 211	72.503	12.712
9281011	72.511	12.764
9281811	72.523	12.823
929 211	72.537	12.885
9291011	72.552	12.949
9291811	72.566	13.013
930 211	72.580	13.077
9301011	72.593	13.138
9301811	72.604	13.195
10 1 211	72.612	13.246
10 11011	72.617	13.293
10 11811	72.618	13.332
10 2 211	72.616	13.362
10 21011	72.611	13.382
10 21811	72.603	13.396
10 3 211	72.593	13.409
0 0 0	0.000	0.000
0 0 0	0.000	0.000
10111811	72.164	13.526
1012 211	71.988	12.909
10121011	72.038	13.102
10121811	72.030	13.106
1013 211	72.022	13.111
10131011	72.015	13.117
10131811	72.008	13.121
1014 211	72.001	13.125
10141011	71.995	13.124
10141811	71.988	13.117
1015 211	71.982	13.107
10151011	71.977	13.094
10151811	71.972	13.080
1016 211	71.967	13.063
10161011	71.961	13.044
10161811	71.954	13.018
1017 211	71.946	12.984
10181011	71.935	12.944
10181811	71.924	12.901
1019 211	71.912	12.856
10191011	71.900	12.810
10191811	71.887	12.762
1020 211	71.886	12.781
10231011	71.941	13.174
0 0 0	0.000	0.000
0 0 0	0.000	0.000
10291811	72.473	15.305

MMDDHHMM	LAT	LON
1030 211	72.493	15.382
10301011	72.504	15.452
10301811	72.511	15.507
1031 211	72.517	15.546
10311011	72.521	15.577
10311811	72.521	15.602
11 1 211	72.518	15.624
11 11011	72.514	15.641
11 11811	72.509	15.658
11 2 211	72.505	15.676
11 21011	72.519	15.730
11 21811	72.540	15.790
0 0 0	0.000	0.000
0 0 0	0.000	0.000
11 61811	72.653	16.349
11 7 211	72.642	16.362
11 71011	72.639	16.382
11 71811	72.631	16.393
11 8 211	72.622	16.404
11 81011	72.614	16.414
11 81811	72.605	16.424
11 9 211	72.596	16.434
11 91011	72.586	16.442
11 91811	72.574	16.450
1110 211	72.562	16.457
11101011	72.550	16.464
11101811	72.537	16.470
1111 211	72.524	16.475
11111011	72.508	16.475
11111811	72.489	16.477
0 0 0	0.000	0.000
0 0 0	0.000	0.000
11151811	72.600	17.017
1116 211	72.592	17.047
11161011	72.574	17.056
11161811	72.559	17.065
1117 211	72.544	17.074
11171011	72.528	17.082
11171811	72.512	17.089
1118 211	72.495	17.095
11181011	72.477	17.101
11181811	72.459	17.106
1119 211	72.441	17.112
11191011	72.454	17.135
11191811	72.456	17.164

APPENDIX D

AR48 POSITIONS

Positions of AR48 from 26 October 1989 to 1 November 1989. Rows of zeros are used to delineate breaks in the tracking record. The format of the data is month day hour minute, latitude, longitude as shown below. Negative longitudes represent westerly longitudes.

MMDDHHMM	LAT	LON
10301802	78.235	-8.225

MMDDHHMM	LAT	LON
1026 41	72.889	-6.201
1026 841	72.900	-6.218
10261641	72.902	-6.216
1027 41	72.907	-6.228
1027 841	72.906	-6.221
10271641	72.909	-6.224
1028 41	72.912	-6.232
1028 841	72.917	-6.243
10281641	72.920	-6.254
1029 41	72.841	-6.254
1029 841	72.849	-6.277
10291641	72.854	-6.303
1030 41	72.849	-6.314
1030 841	72.845	-6.334
10301641	72.844	-6.354
1031 41	72.833	-6.350
1031 841	72.834	-6.384
10311641	72.834	-6.418
11 1 41	72.832	-6.443
11 1 841	72.829	-6.467
11 1 841	72.829	-6.467
11 1 841	72.829	-6.467

APPENDIX E

MZ83 POSITIONS

Positions of MZ83 from 9 MAY 1990 to 28 JUNE 1990. Rows of zeros are used to delineate breaks in the tracking record. The format of the data is month day hour minute, latitude, longitude as shown below. Negative longitudes represent westerly longitudes.

MMDDHHMM	LAT	LON
10301802	78.235	-8.225

MMDDHHMM	LAT	LON
5 91032	73.258	-11.498
5 91832	73.281	-11.424
510 232	73.304	-11.341
5101032	73.319	-11.331
5101832	73.321	-11.326
511 232	73.317	-11.321
5111032	73.312	-11.308
5111832	73.307	-11.282
512 232	73.306	-11.237
5121032	73.310	-11.190
5121832	73.313	-11.142
513 232	73.317	-11.094
5131032	73.325	-11.048
5131832	73.338	-10.998
514 232	73.355	-10.947
5141032	73.373	-10.898
5141832	73.392	-10.860
515 232	73.411	-10.833
5151032	73.429	-10.805
5151832	73.447	-10.779
516 232	73.464	-10.758
5161032	73.478	-10.733
5161832	73.483	-10.711
517 232	73.483	-10.699
5171032	73.482	-10.695
5171832	73.481	-10.683
518 232	73.481	-10.655
5181032	73.484	-10.611
5181832	73.493	-10.566
519 232	73.510	-10.521
5191032	73.531	-10.477
5191832	73.554	-10.443
520 232	73.579	-10.427
5201032	73.602	-10.418
5201832	73.623	-10.402
521 232	73.635	-10.370
5211032	73.637	-10.303
5211832	73.630	-10.174
522 232	73.620	-10.008
5221032	73.609	-9.825
5221832	73.599	-9.638
523 232	73.596	-9.457
5231032	73.602	-9.293
5231832	73.608	-9.174
524 232	73.613	-9.105
5241032	73.616	-9.052
5241832	73.619	-9.004
525 232	73.623	-8.954
5251032	73.630	-8.901
5251832	73.639	-8.850
526 232	73.647	-8.812
5261032	73.651	-8.787
5261832	73.646	-8.762
527 232	73.640	-8.751
5271032	73.632	-8.756
5271832	73.625	-8.760
528 232	73.620	-8.777
5281032	73.616	-8.817
5281832	73.616	-8.870
529 232	73.619	-8.922

MMDDHHMM	LAT	LON
5291032	73.621	-8.958
5291832	73.623	-8.977
530 232	73.625	-8.996
5301032	73.625	-9.015
5301832	73.624	-9.022
5311032	73.623	-9.014
5311832	73.623	-9.005
6 1 232	73.624	-9.003
6 11032	73.623	-9.024
6 11832	73.622	-9.052
6 2 232	73.621	-9.077
6 21032	73.622	-9.077
6 21832	73.628	-9.049
6 3 232	73.635	-9.012
6 5 232	73.641	-8.975
6 51032	73.623	-9.102
6 51832	73.612	-9.326
0 0 0	0.000	0.000
0 0 0	0.000	0.000
6 81032	73.621	-9.338
6 81832	73.598	-9.476
6 9 232	73.595	-9.585
6 91032	73.594	-9.591
6 91832	73.594	-9.582
610 232	73.593	-9.573
6101032	73.593	-9.563
6101832	73.592	-9.554
611 232	73.568	-9.817
6111032	73.590	-9.726
0 0 0	0.000	0.000
0 0 0	0.000	0.000
6251832	73.481	-11.112
626 232	73.476	-11.146
6261032	73.473	-11.180
6261832	73.487	-11.146
627 232	73.507	-11.077
6271032	73.519	-11.076
6271832	73.506	-11.226
628 232	73.492	-11.378

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Seattle, WA 98115

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Universitat Hamburg
Attn : Dr. Jens Meincke
2000 Hamburg 54
Federal Republic of Germany

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Alfred Wegener Institute
for Polar and Marine Research
Am Handelshaven 12
D-2850 Bremerhaven
Federal Republic of Germany